2022

The assessment of movement demands and neuromuscular fatigue in female softball players

Kathryn Cardwell
Edith Cowan University

Recommended Citation

Cardwell, K. (2022). *The assessment of movement demands and neuromuscular fatigue in female softball players*. https://ro.ecu.edu.au/theses/2501

The assessment of movement demands and neuromuscular fatigue in female softball players

This thesis is presented for the degree of

Doctor of Philosophy

Kathryn A. Cardwell

Edith Cowan University
School of Medical and Health Sciences
2022

ABSTRACT

Softball has experienced an increase in worldwide popularity over the last 15 years, and it is expected to rise following the reinstatement of softball as an Olympic sport in 2021. Previous softball research has primarily focused on the biomechanical characteristics of its athletes. However, there is a current lack of research concerning the movement demands occurring in gameplay and the development of neuromuscular fatigue in softball players during sport-specific movements, training sessions, or in competition play. Prior research has demonstrated that a majority of power generated during a bat swing or overhand throw comes from the lower body, with the hip musculature playing an essential role in stabilisation and kinetic energy transmission. Understanding the development of neuromuscular fatigue, particularly in the hip musculature of softball athletes, will allow coaches and sport scientists to optimise training sessions, athlete monitoring techniques, and recovery methods. Accordingly, the overall aims of this thesis were to 1) describe the movement demands of female softball players during defensive and offensive gameplay, with a focus on the frequency and duration of movements occurring and differences between positional groups; 2) determine the reliability of the ForceFrame Hip Strength Testing System in assessing hip and shoulder strength of female softball players unaccustomed to isolated joint isometric measures; 3) assess changes in isometric hip strength in female softball players caused by a repeated batting protocol; and 4) compare changes in isometric strength of female softball players in training and game settings. The outcomes of this thesis will help to establish a description of the movement demands of softball games, which may optimise future softball training and recovery methods. Additionally, data gathered in this thesis will provide a solid foundation for conceptualising neuromuscular fatigue in softball players. These results will thus allow for a greater understanding of athlete preparation.

Study one determined that softball is primarily composed of low intensity activities, like standing or walking, with intermittent periods of high intensity activity (e.g. sprinting, bat swings, high intensity throws). The cumulative effect of these high intensity activities across game durations of two hours or greater, compact tournament schedules and environmental factors may amplify neuromuscular fatigue. Study two concluded that the ForceFrame was a reliable tool in assessing hip and shoulder isometric strength in female diamond-sport athletes, potentially providing sport scientists with a suitable alternative to handheld dynamometers in field-based isometric testing. Study three documented changes in electromyographic amplitude and median frequency, isometric hip strength, and batted ball velocity of female softball players during a repeated batting protocol. Results indicate repeated batting can lead to neuromuscular fatigue and underscores the importance of routine monitoring of softball players in settings with limited recovery. Results of study four demonstrated significant levels of fatigue following softball training and gameplay, as well as evidence of cumulative fatigue in softball players following several games during a multi-day tournament. The results of this study provide the groundwork for determining an appropriate balance between competition-level training and adequate recovery.

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

i. incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher education;
ii. contain any material previously published or written by another person except where due reference is made in the text of this thesis; or
iii. contain any defamatory material.
iv. I also grant permission for the Library at Edith Cowan University to make duplicate copies of my thesis as required.

[redacted]

Kathryn A Cardwell
24/08/21

COPYRIGHT AND ACCESS STATEMENT

ACKNOWLEDGEMENTS

These past three and a half years have been quite a ride, with many highs and lows, and I am incredibly thankful for the support and encouragement that I have received along the way.

To my supervisors, Prof Sophia Nimphius, Dr Krissy Kendall, and Dr Jodie Cochrane Wilkie – I would have been at a loss without your assistance and guidance. Soph, I'm so grateful that you reached out to me in 2016 and invited me to come work with you and Softball WA. The amount that I have learned from you cannot be expressed. Thank you for this opportunity. Krissy, you're the best. I've loved working with you over these last three and half years. You have no idea how much I appreciated your willingness to pause your work and let me run something by you or ask for help on statistics stuff. Thank you for your dedication, your time, and your friendship. Jodie, I will forever be thankful that you were willing to join this project midway through. Your input and guidance on biomechanics, EMG, and time-motion related stuff were so greatly appreciated. It has been a pleasure working with you and I hope this will not be the last of our collaborations.

To the girls from the Western Flames Softball team – I am so thankful that I had the opportunity to work with such dedicated and enjoyable athletes. Working with you all was a highlight of my time in Australia. I am eternally grateful that everyone was happy to volunteer as subjects for my random projects. In particular, Shannon, Tikki, Riou, Liv, and Mac, you guys went above and beyond in volunteering, and I'm so thankful for your friendship and the ability to count on you when I needed help. You sincerely are legends. To my research subjects outside of Softball WA, I am also grateful for your willingness to step up and either be a guinea pig as I piloted one of my studies or were part of data collection. After working in research for years and years, I know precisely how indispensable volunteers like you all are. Thank you for your help.

To my amazing research assistants, Mitchell Roberts and Jonathan Gundel –I could not have asked for more helpful and more engaging assistants. I'm so glad that we got the opportunity to work together, and hope you guys learned a bit about sports analysis and EMG data collection. I loved teaching and working with you both and I'm looking forward to seeing what the future has in store for you both.

To my trivia teammates – Grant and Jo, Clay and Laura, Tony, Josh, Jake, Angelo, Renee and Ellie. You all were my saving grace in the middle of the week. It was so satisfying to be able to put academics aside for a few hours and brainstorm on what's the next line of song lyrics. I loved my time with you all and hope I can find or establish a new trivia team as good as Nipple Oscillation Factor.

To my family – Mom and Daddy, words cannot express how much your encouragement and love has kept me going. I've worked so hard to be successful, and you have both told me again and again how proud of me you are. Those words lifted me out of some dark times, and I could not have asked for better parents. Likewise, Kristine and Anna, I could not have asked for better sisters. The two of you were always available for a chat or text message, and I can't even recall the number of times that I cried to one of you on the phone. But with your encouragement and support, I'm finally at the end of this crazy journey. Thank goodness. I love you both and look forward to all of the future sister weekends and sangria parties we have in the future.

Finally, to my partner, Felicia – you should get an honorary PhD for everything you have done for me. I'm so grateful that you responded to my message way back in October 2017. You've been there for me from the very beginning of this journey, and I could not have wished for anyone better. I could not have done this without your love, support, encouragement, your willingness to read my papers so many times you could recite them, and your ability to push me to work when I didn't want to. I love you and I can't wait to see where life takes us next.

TABLE OF CONTENTS

General Introduction and Aims of the Thesis

Sets out the research objectives and provides an overview of the thesis structure

Review of the Literature

Discusses the main emphasis of prior research and summarises key findings that underpin the design and implementation of the current research

Time-Motion Analysis of Female Softball Players During a National Tournament

Reliability of Isolated Hip and Shoulder Strength Measures in Female Athletes

Neuromuscular Fatigue Development in Female Softball Players During a Repetitive Batting Protocol

Changes in Isolated Hip Strength Following Training and Gameplay in Female Softball Players

General Summary and Conclusion

Summarises research findings and offers suggestions for future avenues of research

LIST OF TABLES

LIST OF FIGURES

LIST OF ABRREVIATIONS

Abbreviation	**Definition**
°	Degree
ABD	Abduction
ADD	Adduction
AL	Adductor longus
ANOVA	Analysis of variance
BBV	Batted ball velocity
C	Catcher
CI	Confidence interval
cm	Centimetre
CV	Coefficient of variance
EMG	Electromyography
ER	External rotation
GM	Gluteus medius
GPS	Global Positioning System
H	Hip
HHD	Handheld dynamometer
HI	High intensity
Hz	Hertz
ICC	Intra-class correlation
IF	Infield
IR	Internal rotation
kg	Kilograms
$km.h^{-1}$	Kilometres per hour
L	Left-handed
LI	Low intensity
m	Metre

MVIC	Maximal voluntary isometric contraction
MDF	Median frequency
N	Newton
n	Number
OF	Outfield
p	Significance
P	Pitcher
PSD	Power spectral density
R	Right-handed
RMS	Root mean square
RPE	Borg Rating of Perceived Exertion
S	Shoulder
s	Seconds
sEMG	Surface electromyography
SD	Standard deviation
SEM	Standard error of measurement
SWC	Smallest worthwhile change
TEM	Typical error of measurement
TFL	Tensor fascia latae
TMA	Time-motion analyses
V	Volts
yrs	Years

CHAPTER ONE

General Introduction and Aims of the Thesis

Sets out the research objectives and provides an overview of the thesis structure

1.1 Background

The global popularity of softball has increased dramatically over the last 15 years, with an estimated 65 million people in over 140 countries playing softball or baseball (World Baseball Softball Confederation, 2017). Many believe that with the reinstatement of softball as an Olympic sport in 2021, interest will continue to rise. Previously, softball research has primarily focused on the physiological characteristics of its athletes (Cahill & Jones, 2010; Lowe et al., 2010; Nimphius, 2011b; Nimphius et al., 2010, 2012; Terbizan et al., 1996), biomechanical analyses of the windmill pitch (Barrentine et al., 1998; Forshaw et al., 2013; Guido Jr. et al., 2009; Maffet et al., 1997; Minetos et al., 2020; Nimphius et al., 2016; Oliver & Plummer, 2011; Remaley et al., 2015; Werner et al., 2017) or the relationship between upper body strength and bat swing velocity (Messier, 1982; Reilly-Boccia et al., 2015; Teichler, 2010; Weimer et al., 2007). However, there is a current lack of research concerning neuromuscular fatigue in softball players, so it is important to also understand the movement demands of the game and then determine and gain understanding of fatigue during sport-specific movements, training sessions, or competition play.

Neuromuscular fatigue is defined as any exercise-induced reduction in the ability to produce force or power within a muscle or muscle group (Taylor et al., 2016). Extensive research has demonstrated a reduction of force in the lower body following gameplay in sports like Australian Rules Football (Buchheit et al., 2017), soccer (Cortes et al., 2012; Paul et al., 2014; Wollin, Pizzari, et al., 2018), and rugby (Roe, Phibbs, et al., 2016). Though softball's physical demands may not be as strenuous as running-dominant sports such as these, its average game durations of longer than two hours, continuous anticipation and concentration during gameplay and the repetitive nature of frequent maximal-effort movements may exacerbate neuromuscular fatigue development. Research has also confirmed playing performance declines as a result of neuromuscular fatigue in cricket and baseball (Christie, 2012; Escamilla et al., 2007; Freeston et al., 2014; Murray et al., 2001; Tripp et al., 2007; Veness et al., 2017), two sports with intermittent gameplay similar to softball. To better prepare softball athletes for fatiguing gameplay or training sessions, research must look deeper into neuromuscular fatigue development in softball players.

To understand fatigue in softball, research is firstly required into the movement demands of softball, as there is currently limited research in this area. Time-motion analyses (TMA) are one effective method of quantifying movements during sporting events, providing sport scientists with a comprehensive view of the physical demands athletes face during competition. Previous research applying TMA have primarily investigated: distance covered during match play (Coutts et al., 2010; Wisbey et al., 2010), repeated-sprint activities (Spencer et al., 2004; Spencer et al., 2005), work-to-rest ratios (D'Auria & Gabbett, 2008; Deutsch et al., 2007) and differences in movement by position (Deutsch et al., 2007; Spencer et al., 2005; Virr et al., 2014). Except for one study tracking throwing volumes during collegiate softball games (Axe et al., 2002), there have been no TMA studies to date for softball games at any level. While batting and throwing are considered primary movements in softball, other movements like jumping, sprinting, and lateral movements may also play a significant role in neuromuscular fatigue development. A detailed time-motion analysis of softball gameplay may allow sport scientists to understand further why neuromuscular fatigue may develop.

Along with understanding game demands, monitoring fatigue levels is of paramount importance. Athlete monitoring measures are commonly employed to assess player recovery following training or competition (Halson, 2014; McGuigan et al., 2020; Ryan et al., 2019). A 2012 survey of high performance practitioners in New Zealand and Australia reported that 61% of respondents implemented weekly or monthly performance tests (e.g. jump tests, isometric measures, strength evaluations) for fatigue monitoring (Taylor et al., 2012). In particular, isometric strength measures have broad utility in the assessment and monitoring of athletes (Roe, Phibbs, et al., 2016; Skillington et al., 2017; Wollin, Pizzari, et al., 2018), as they provide insight into the timing and location of neuromuscular fatigue development (Babault et al., 2006). However, the reliability and validity of the equipment used for these measures must be known, as well as the determination of sport-specific testing measures.

Though softball movement demands remain somewhat unknown, softball players regularly perform complex whole-body movements such as jumping, sprinting, throwing and batting which transfer angular momentum up through the kinetic chain from the lower extremities, to the trunk and upper extremities. The muscles of the hips and pelvis are responsible for the stability of the body during these types of actions. Consequently, research has been undertaken to investigate isometric hip strength as a measure of neuromuscular fatigue in running-dominated sports like rugby, soccer, and Australian football (Buchheit et al., 2017; Crow et al., 2010; Fulcher et al., 2010; Roe, Phibbs, et al., 2016; Ryan et al., 2018; Thorborg et al., 2011; Wollin, Pizzari, et al., 2018). However, there is a gap in research relating to isometric hip strength for diamond-based sports like softball or baseball. Studies have shown that 50% of the energy generated in an overhand throw arises from the lower body (Kibler et al., 2006). Further, the generation of force during a bat swing is conveyed up the kinetic chain through the legs, as demonstrated in baseball (Fortenbaugh, 2011; Shaffer et al., 1993; Welch et al., 1995). Therefore, repetitive tasks like batting and throwing have the potential to reduce neuromuscular function and impact performance.

In addition to isometric strength testing, electromyography (EMG) may provide a local estimation of neuromuscular fatigue of specific muscles. Currently, studies using EMG on softball players have focused on the muscles of the upper body (Chang et al., 2010; Remaley et al., 2015; Rojas et al., 2009) or have detailed lower body activation in position-specific movements (e.g. catchers rising from a squat, the windmill pitch) (Oliver & Plummer, 2011; Plummer & Oliver, 2014). However, due to the involvement of the lumbopelvic-hip complex in pelvic stability during energy transfer from the lower extremities to the upper extremities (Gilmer et al., 2018; Oliver, 2014; Oliver & Keeley, 2010; Plummer & Oliver, 2014; Washington et al., 2018), it is necessary to assess changes within specific hip musculature of softball players in response to neuromuscular fatigue. As softball players are likely to perform numerous bat swings throughout a game and more so during training, this movement may significantly contribute to fatigue development. Additionally, unlike position-specific demands (e.g. pitching, catchers squat), nearly all playing positions bat, making batting a universal contribution of fatigue development. A combined analysis of changes in isometric strength and EMG waveforms (e.g. amplitude and median frequency) of the hip musculature of softball players intermittently from batting may provide further insight into neuromuscular fatigue development and its impact on performance variables (e.g. batted ball velocity).

Research is also required to assess differences in intensity and workload in training and competition settings for softball players. Though softball games are interspersed with low to moderate intensity periods of play (*General Physical Activities Defined by Level of Intensity*, 2011), it is not uncommon for softball training sessions to be more consistently active, with skills training, batting practice, and simulated gameplay. Research has established that training sessions in cricket often surpass the workload demands of those experienced during competition (Vickery et al., 2018). Other investigations have demonstrated that amongst cricket playing positions, seam bowlers experienced significantly higher workloads in training than non-bowlers due to their involvement in batting, fielding and bowling drills (Cooke et al., 2019). One could infer a similar result for softball players who participate in batting and fielding drills in every training session. As training sessions are likely to occur more frequently than competition, scheduling an appropriate amount of recovery following intense training may help prevent overtraining and the risk of injury or illness for softball athletes. Indeed, Patel et al. (2021) have determined that more softball injuries occur in training than in gameplay. Condensed tournament schedules and multiple games within a day may further increase neuromuscular fatigue. An analysis must first compare neuromuscular fatigue development following training and single games or tournament play to appropriately prescribe recovery for softball athletes.

1.2 Aims of the Research Studies

As a result of current gaps in the literature, this thesis seeks to:

a) assess softball players' movement demands during offensive and defensive gameplay, focusing on the frequency and duration of movements and differences between positional groups;
b) examine the test-retest reliability of the ForceFrame Hip Strength Testing System (Vald© Performance, Newstead, QLD, AUS) in female diamond-sport athletes unaccustomed to isolated joint isometric assessments in the hip or shoulder regions, and examine the inter-method agreement of the ForceFrame and a handheld dynamometer (HHD);
c) assess neuromuscular fatigue development measured by isometric force and EMG in hip strength assessments of female softball players intermittently during a repeated batting protocol and evaluate changes in performance variables (e.g. batted ball velocity, RPE) caused by fatigue;
d) compare fatigue levels between a training session and gameplay on hip adductor and abductor strength and to confirm evidence of cumulative fatigue development during tournament play.

1.3 Research Questions and Hypotheses

Study One – *A Time-Motion Analysis of Female Softball Players during a National Tournament*

Question 1: What are the movement demands of female softball players during a national tournament?

Hypothesis 1: Softball gameplay will be of moderate intensity, interspersed with periods of high-intensity activity. The demands of the sport will vary by positional group, with the pitcher and catcher performing more throwing movements but less walking or running than the infielders or outfielders.

Study Two – *Reliability of Isolated Hip and Shoulder Strength Measures in Female Athletes*

Question 1: Does the ForceFrame have acceptable reliability when measuring isolated hip and shoulder strength in female softball players?

Hypothesis 1: The ForceFrame will demonstrate acceptable reliability when measuring isolated hip and shoulder strength of female softball players.

Question 2: How does the reliability of the ForceFrame compare to previously documented data using handheld dynamometers?

Hypothesis: In line with previous research (O'Brien et al., 2019), the reliability of the ForceFrame will be similar to that of handheld dynamometers.

Study Three – *Neuromuscular Fatigue Development in Female Softball Athletes during a Repetitive Batting Protocol*

Question 1: How does the median frequency and amplitude of EMG waveforms in the hip adductor and abductor muscles of female softball players change with fatigue during a fatiguing batting protocol?

Hypothesis 1: It is hypothesised that the median frequency will shift toward lesser frequencies and the EMG amplitude will increase as a result of neuromuscular fatigue in the hip adductor and abductor muscles of female softball players during a fatiguing batting protocol.

Question 2: How will isometric hip strength change with fatigue during a fatiguing batting protocol?

Hypothesis 2: We also hypothesise that isometric hip strength during hip adduction and hip abduction will decrease throughout the protocol.

Question 3: How will batted ball velocity and ratings of perceived exertion (RPE) change during a fatiguing batting protocol?

Hypothesis 3: Developing neuromuscular fatigue will lead to decreases in batted ball velocity and increases in RPE throughout the fatiguing batting protocol.

Study Four – *Changes in Isometric Hip Strength Following Training and Gameplay in Female Softball Athletes*

Question 1: Do significant levels of fatigue develop in female softball players during training and gameplay?

Hypothesis 1: It is hypothesised that significant levels of fatigue will develop in the training and gameplay settings and

Question 2: Is there evidence of a cumulative effect of fatigue following multiple games within a tournament setting?

Hypothesis 2: We hypothesise there will be evidence of cumulative fatigue following multiple games within a tournament setting.

1.4 Significance of the Research

With the increasing popularity, and hence, a greater number of athletes participating at all levels of the sport, an understanding of the game's characteristics can better inform softball practice planning and athlete health welfare protocols. Compacted tournament schedules and average game durations of greater than two hours may exacerbate fatigue development, particularly in less conditioned athletes. As the success or failure of a single play may dictate the outcome of softball games, it would be beneficial for coaches to have fatigue management strategies to reduce athlete performance declines. This thesis is taking the initial steps in understanding the demands of softball, which will provide coaches and sport scientists a greater understanding of athlete readiness and recovery.

1.5 Limitations

The limitations of this thesis are as follows:

Study One – *A Time-Motion Analysis of Female Softball Players during a National Tournament*

a) Individual idiosyncrasies or movement habits

Analysis of movements during gameplay is subject to individual idiosyncratic movements or personal habits of the athlete (e.g. pacing between plays, jumping after each pitch), where variability could cause an increase in specific movements that are not directly related to gameplay. However, all movements were analysed in this study, regardless of the reason or how it may have influenced the data.

b) Game score

The frequency and duration of movements during gameplay may have changed depending upon the score of the game (i.e. behind in score leading to more defensive play). As the selected team placed 3rd in the national tournament with a win-loss record of 5-7, the varied outcomes of the games played covered a broad spectrum of scenarios (e.g. high scoring games, significant losses) which may have lessened this impact.

c) Exclusion of warm-up or cool-down activities

The analysis was conducted on events occurring during gameplay only, omitting warm-up and cool-down activities. While the addition of movements occurring during warm-up and cool-down may help investigate cumulative fatigue throughout complete game-day preparation and play, the scope of this investigation analysed movements occurring during the game only.

Study Two – *Reliability of Isolated Hip and Shoulder Strength Measures in Female Athletes*

a) Testing scheduling

Attempts were made to keep testing time consistent each session. However, not all subjects were able to return consistently due to scheduling conflicts. Therefore, the diurnal schedules of those athletes may have been affected. In attempts to mitigate this effect, submaximal warm-up contractions preceded testing.

b) Maximal effort contractions

The nature of maximal effort contractions lends to the possibility of fatigue impacting later tests. Recovery periods of 30 seconds took place between trials, but it is uncertain if fatigue from previous efforts impacted later tests.

c) Subjects from different sports

The majority of the subjects were softball players, however, several female subjects from a local state-level baseball team were tested due to recruitment difficulties. Though baseball and softball are sports of similar rules, game format, and common movements, at present it cannot be assumed that the physical characteristics of athletes of the same sex from both sports are comparable.

Study Three – *Neuromuscular Fatigue Development in Female Softball Players during a Repetitive Batting Protocol*

a) Participant numbers

Initial power analysis calculated an appropriate sample size of 11 subjects (α= ≤0.05, 1- β= 0.8). Due to the impact of COVID-19, suspension of participant recruitment occurred. The final analysis included four subjects, where the results are written as a case study.

b) Laboratory-based testing

The use of laboratory-based testing may limit the ecological validity of the study. However, laboratory testing allowed for more detailed analysis of the bat swing motion and follows prior literature precedents (Chang et al., 2010; Fortenbaugh, 2011; Shaffer et al., 1993).

c) Use of Isometric Measure to reflect EMG changes during a dynamic task

It has been speculated whether isometric contractions provide a good representation of fatigue development during human movement as fatigue is influenced by contraction type, activity, and duration (Barry & Enoka, 2007; Enoka & Stuart, 1992; Hunter et al., 2004; Kay et al., 2000). However, continuous changes in muscle length and the positioning of electrodes over active motor units during dynamic contractions cause fluctuations in EMG spectral shift that may not be related to fatigue (Beck et al., 2014; Hägg, 1992). The decision to use an isometric measure was based upon the well-established reliability of EMD data during this contraction type (Christ et al., 1994; Fauth et al., 2010; Kellis & Katis, 2008; Sleivert & Wenger; Viitasalo & Komi, 2008), with the assessment of batted ball velocity and RPE to further assess changes during a dynamic movement (i.e. batting).

Study Four – *Changes in Isometric Hip Strength Following Training and Gameplay in Female Softball Players*

a) Timing of testing

Coach's preferences determined the timing of testing; thus, testing occurred in the days leading up to tournament and on the last game of tournament. As a result, we cannot demonstrate how a single game affected the athletes without recognising the influence of multiple games in the previous five days. Further, due to travel schedules, several athletes were tested before and after training on a different day from the rest of the team. Absolute results may vary for these athletes due to factors such as different training intensities, the previous day's airline travel, and time of day for testing. However, the analysis was performed as within person, mitigating at least a portion of this limitation.

1.6 Delimitations

The delimitations of the thesis are as follows:

Study One

a) Sex

Subjects recruited for the current study were restricted to female softball athletes.

b) Playing level

Only subjects currently playing on a state-level softball team were recruited for this study.

Study Two

a) Sex

Subjects recruited for the current study were restricted to female softball and baseball athletes.

b) Playing level

Only subjects currently playing on a state-level team were recruited for this study.

Study Three

a) Sex

Subjects recruited for the current study were restricted to female softball athletes.

b) Playing level

Only subjects currently playing on a state-level softball team were recruited for this study.

Study Four

a) Sex

Subjects recruited for the current study were restricted to female softball athletes.

b) Playing level

Only subjects currently playing on a state-level softball team were recruited for this study.

1.7 General Overview of the Following Chapters

This thesis consists of seven chapters. First, a review of literature is presented in Chapter Two. Subsequently, four experimental studies are presented. Chapter Three includes the results of the first study, which explores the movement demands of softball players during gameplay in a national tournament. Chapter Four contains the second study, which investigates the reliability of the ForceFrame when assessing isometric hip and shoulder strength of female diamond-sport athletes. Chapter Five includes the results of the third study, which assesses changes of median frequency and amplitude of EMG waveforms, isometric hip strength, and performance variables of female softball athletes during a repetitive batting protocol. Chapter Six includes the fourth study, which evaluates the development of fatigue during training sessions and gameplay and any cumulative effect of fatigue in a tournament setting. Chapter Seven contains a general summary and conclusion to the entire thesis.

CHAPTER TWO

Review of the Literature

Discusses the main emphasis of prior research and summarises key findings that underpin the design and implementation of the current research

2.1 Background

There is a current lack of research concerning the movement demands occurring in gameplay and the development of neuromuscular fatigue in softball players during sport-specific movements, training sessions, or in competition play. Further investigations of neuromuscular fatigue development, particularly in the hip musculature of softball athletes, will allow coaches and sport scientists to optimise training sessions, athlete monitoring techniques, and recovery methods. The following chapter presents relevant literature on this project. It is divided into six sections presenting introductory details of softball gameplay, TMA as a method of quantifying movement demands, an explanation of neuromuscular fatigue, methods of assessing neuromuscular fatigue, the development of fatigue in various playing formats, and a summary of conclusions from this review and applications to this project.

2.2 Softball Gameplay and Movement Mechanics

A softball game is played between two teams of nine players, each alternating between fielding and batting. Typically lasting seven innings, the game's objective is to score more runs while batting than the other team by the last completed inning. In Australia, the state-level softball season occurs in the spring, beginning in September and culminating with the National Tournament in early January. Other universal sports, such as Rugby Sevens or the Union of European Football Association (UEFA) Champions League Football conclude protracted seasons with the most critical performances occurring in a tournament that is generally spread across several weeks and incorporates several rest days between matches (*2018/19 Champions League match and draw calendar*, 2018; *HSBC Sevens Series Rounds*, 2018). In contrast, softball games are often played as part of a condensed tournament schedule across several days rather than throughout a lengthy season. The Women's World Championship lasts nine to ten days (*Softball Australia Archived Events*, n.d.), and the 2021 Olympics tournament will occur over six days (*Softball Olympic Games 2021 Schedule*, 2020). Additionally, it is not uncommon for players to participate in multiple games per day. In the 2019 Australian Open Women's National Championship (the "Gilley's Shield"), teams played, on average, two games a day for seven days, depending on tournament standing (*Softball Australia Archived Events*, n.d.).

At present, research has yet to produce a comprehensive analysis of movements that occur during softball gameplay. Regardless of this fact, numerous studies have detailed the kinematics and kinetics of two of the most common movements, batting and overhand throwing. In these movements, softball players utilise the kinetic chain to transfer angular momentum from the ground up through the lower extremities, trunk and upper extremities. Skills such as these require the sequential, proximal-to-distal movement of joint segments to facilitate the ballistic nature necessary to throw out a baserunner or hit the ball to the outfield (Flyger et al., 2006). A vital component of the successful energy transfer from the lower to upper extremities relies on optimal stabilisation by the muscles of the hips and pelvis, specifically the glutei muscles, hip abductors and hip adductors (Gilmer et al., 2018; Washington, 2018). Shaffer and colleagues (1993) report that "the uncoiling of the wound-up pelvis, trunk, and upper extremities on a stable base provides the power for the baseball batting swing". Indeed, pelvic stability during a bat swing allows for maximum pelvis rotation velocities of 714°/s and maximum upper trunk and arm rotation velocities of 937°/s and 1160°/s, respectively (Welch et al., 1995). Previous research has suggested that the mechanics of proximal body segments (e.g. the legs, hips, trunk) may influence the movements of distal body segments (e.g. the shoulder, elbow, wrist) (Kibler et al., 2006; Oliver & Keeley, 2010; Plummer & Oliver, 2014; Washington, 2018). Kibler (1998) reported that a 20% decrease in kinetic energy from the hips and trunk during an overhand task like a throw would require a 34% increase in rotational velocity at the shoulder to produce the equivalent amount of force the hand. Unquestionably, the hips and pelvis muscles play a significant role in angular momentum transfer through the kinetic chain, and instability or weakness in these muscles may increase injury susceptibility. Therefore, an understanding of the movements used and the demands of these movements in softball gameplay is needed to develop sport-specific training for all positions and movements.

2.3 Time-Motion Analyses

The determination of movement demands during softball gameplay is crucial to establishing specialised training and conditioning programs, and time-motion analyses are an effective and reliable method of quantifying movements during sporting events (Duthie et al., 2003). Prior studies in various sports have used this method to investigate distance covered during match play (Coutts et al., 2010; Wisbey et al., 2010), repeated-sprint activities (Spencer et al., 2004;

Spencer et al., 2005), work-to-rest ratios (D'Auria & Gabbett, 2008; Deutsch et al., 2007) and differences in movements by position (Bloomfield et al., 2007; Deutsch et al., 2007; Spencer et al., 2005; Virr et al., 2014). Many time-motion analyses focus on running-dominant sports like rugby, Australian Rules Football or soccer. However, the demands of these sports are vastly different from softball, and as such, details from such research cannot be directly applied.

Conversely, cricket has a similar intermittent start-stop nature as softball, and several time-motion analyses have evaluated the demands of cricket. Duffield and Drinkwater (2008) compared movement patterns and changes of activity of batters during Test or One-Day matches. The authors determined that, though cricket incorporates more low intensity activities (e.g. standing, walking) than other running-dominant sports, the amount of sprinting and striding is comparable to that found in a Super 12 rugby match or a field hockey game. In a cricket Test century, durations of high intensity movements were also similar to those reported in soccer, field hockey, and rugby union (1-2 seconds compared to 2-3 seconds, respectively) (Duffield & Drinkwater, 2008). Movement patterns between different playing positions across three cricket match formats (Twenty20, One-Day, and multi-day matches) have also been compared (Petersen et al., 2010). Across all match formats, fast bowlers exhibited the greatest workload compared to wicket-keepers, spin bowlers and fielders, covering 20-80% greater distance, up to 8x more frequent sprints, and at least 35% less recovery time between high intensity efforts. Additionally, despite the intermittent nature of cricket, distances covered by all positions ranged from an average of 4.45 km in Twenty20 matches to ~18.1 km in multi-day matches (Petersen et al., 2010). Despite cricket historically being considered a low intensity sport (Rudkin & O'Donoghue, 2008), these studies indicate that the physiological demands of lengthy cricket match formats and repetitive movements may be as significant as other running-dominant sports like soccer or rugby.

While softball is currently considered to be a sport of low to moderate intensity (*General Physical Activities Defined by Level of Intensity*, 2011), time-motion analyses similar to those by Duffield and Drinkwater (2008) and Petersen et al. (2010) could provide a greater understanding of the activity and movement demands occurring within softball gameplay and lead to the creation of sport-specific training for all positions and movements. To date, only one study has completed a time-motion analysis of collegiate softball gameplay. Axe et al. (2002) determined that a typical collegiate softball pitcher throws an average of 89.6 pitches per game, while infielders, outfielders, and catchers combine to make an average of 31.8 high effort throws per game. The authors used this data to generate interval-based throwing programs to rehabilitate players based on position. However, their report does not include analysis of movements such as running, jumping, bat swings, or other frequent activities that occur during a softball game, nor does it address training for uninjured softball players. As softball players perform countless high intensity activities throughout a game (e.g. bat swings, sprints, throws), neuromuscular fatigue caused by the repetitive nature of such maximal-effort movements may disrupt the kinetic chain and hinder efficient energy transmission.

2.4 Neuromuscular Fatigue

Neuromuscular fatigue is defined as any exercise-induced reduction in the ability to produce force or power within a muscle or muscle group (Taylor et al., 2016). This reduction manifests as overall impaired muscle function or a decline in the central nervous system's ability to activate muscle contractions (Carroll et al., 2017). When investigating fatigue, scientists tend to classify neuromuscular fatigue into two separate categories: peripheral fatigue and central fatigue.

Peripheral fatigue occurs within the muscle itself and can be further broken down into impairments at the transmission level of the neuromuscular junction, muscle membrane, and sarcoplasmic reticulum, or at the contractile level (Asmussen, 1979). On the other hand, central fatigue is associated with all spinal and supraspinal factors capable of causing a reduction in motoneuron excitability (Bigland-Ritchie et al., 2000; Carroll et al., 2017; Taylor et al., 2016; Taylor & Gandevia, 2008; Taylor et al., 2006). Overall, neuromuscular fatigue induces the decline of function for many components of the nervous system. These include decreased excitation supplied by the motor cortex (Gandevia, 1998; Gandevia et al., 1996; Smith et al., 2007); fatigue-sensitive muscle afferents limiting voluntary command (Gandevia et al., 1996); decreased descending drive from the motor cortex to the motoneurons (Boyas & Guevel, 2011; Enoka, 2008; Enoka et al., 2011; Taylor et al., 2016; Taylor & Gandevia, 2008); the reduction in recruitment and rate coding (Deschenes, 1989; Taylor et al., 2016); and modifications in neuromuscular transmission, muscle action propagation, excitation-contraction coupling and decreased neurotransmitter release at the post-synaptic membrane (Boyas & Guevel, 2011).

Understanding fatigue mechanisms during sports performance may help coaches and sport scientists adjust player workloads or playing time to facilitate recovery.

Previous research has indicated that low intensity exercise leads to greater central fatigue development than peripheral fatigue (Carroll et al., 2017; Millet & Lepers, 2004; Taylor et al., 2016). Low intensity longer duration exercise also has a greater effect on central fatigue development than high intensity short duration exercise due to more significant declines in voluntary activation (Carroll et al., 2017; Froyd et al., 2016; Goodall et al., 2017; Thomas et al., 2015). Additionally, research suggests that the intermittent start-stop nature of cricket contributes to the early development of central fatigue (Christie, 2012). Finally, high intensity movements such as sprints, vertical jumps, throws and bat swings, although predominately affecting peripheral fatigue, may also contribute to central fatigue factors due to increased motor unit firing rate or recruitment to maintain performance as peripheral fatigue accumulates (Decorte et al., 2012). However, without a detailed description of the movement demands of softball gameplay, future research cannot estimate how much of an impact high intensity movements such as these will play in fatigue development. Neuromuscular fatigue may manifest in physical performance declines measured as reductions in throwing velocities, throwing accuracy and compromised neuromuscular control, as has been previously demonstrated in baseball (Escamilla et al., 2007; Freeston et al., 2014; Murray et al., 2001; Tripp et al., 2007). As softball games typically last two hours and are considered an intermittent-activity sport (McArdle et al., 2015), it may be that softball players are more susceptible to neuromuscular fatigue, and tournament schedules (with many games scheduled within a short time frame) may compound fatigue accumulation. This speculation supports the need for the implementation of routine athlete monitoring methods, especially during competitive gameplay.

2.5 Assessment of Neuromuscular Fatigue

In high performing athletic populations, monitoring is commonly employed to assess athletes' recovery from neuromuscular fatigue following training or competition (Halson, 2014; McGuigan et al., 2020; Ryan et al., 2019). A 2012 survey of high-performance practitioners in New Zealand and Australia indicated that 61% of respondents used some form of performance test (e.g. jump tests, sport-specific performance assessments, strength tests) weekly or monthly for fatigue monitoring (Taylor et al., 2012). Although there are several ways in which coaches can assess an athlete's readiness to play, monitoring fatigue levels is of paramount importance due to how it affects performance. The following sections will address selected methods for assessing neuromuscular fatigue.

2.5.1 Electromyography

One of the commonly used measures in research to assess neuromuscular fatigue at peripheral locations is electromyography (EMG), which is the measure of the electrical activity of the selected muscle. The amplitude and frequency of spikes of the raw EMG demonstrate the recruitment and the rate of stimulation of activated motor units (Konrad, 2005). Fast-twitch muscle fibres fire at a higher frequency than slow-twitch muscle fibres (30-50 Hz compared to 10-20 Hz, respectively) (Cram, 2011). EMG analysis is often undertaken during maximal voluntary contractions (MVCs) to assess fatigue, as fatigue is generated rapidly and neural input by all motoneurons involved in the contraction stress the entire nervous system uniformly (Taylor et al., 2016). During a typical MVC, greater fast-twitch muscle fibre recruitment is represented by a large proportion of frequencies with higher amplitudes in the upper bandwidth on an EMG power spectrum graph. However, during muscle fatigue, the accumulation of hydrogen ions reduces conduction velocity and the excitability of the muscle fibre membrane (Babault et al., 2006; Masuda et al., 1999). As a result, motor unit firing rates and overall force production is reduced while contraction time increases. The depletion of available fast-twitch motor units and greater reliance on slow-twitch motor units causes a shift toward the lower frequencies of the EMG power spectrum, a common indicator of neuromuscular fatigue (Beck et al., 2014; Bigland-Ritchie et al., 1981; Masuda et al., 1999). Figure 1 illustrates the power spectrum shift from higher to lower frequencies in fatigue developed during an isometric contraction.

At the request of the author,

this image is unavailable in this version of the thesis

Figure 1. A comparison of power spectral density of EMG signals with and without fatigue. Median frequencies for the "no fatigue" and "with fatigue" data are indicated with lines at 60 Hz and 50 Hz, respectively. Taken from Tkach et al. (2010).

Several methods have been developed to analyse EMG signals, but median frequency (MDF), the frequency where the EMG power spectrum is divided into two regions with an equal area (Cifrek et al., 2009; Hägg, 1992; Phinyomark et al., 2012), is widely used in assessing muscle fatigue. Median frequency has demonstrated the most accurate conduction velocity estimates compared with other analyses such as mean frequency or the ratio between high and low frequency components (Dilodeau et al., 1995; Pincivero et al., 2001; Roman-Liu, 2016; Stulen & De Luca, 1981). Further, MDF is reliable on a trial-to-trial and day-to-day basis (De Luca et al., 1983), and is less affected by noise and artefact and influenced by muscle fatigue to a greater degree (De Luca et al., 1983; Stulen & De Luca, 1981).

In addition to MDF, changes in EMG amplitude have also been used to indicate neuromuscular fatigue development. During muscle fatigue, EMG amplitude increases due to changes in motor unit firing rate, recruitment, the shape and synchronisation of motor unit action potentials, and conduction velocity (De Luca, 1979; Gonzalez-Izal et al., 2012). However, factors such as muscle architecture, geometry, EMG cross-talk, and subcutaneous tissue thickness also influence EMG amplitude (Farina et al., 2004). Therefore, amplitude is rarely used individually but rather in combination with other measures, such as spectral analyses like MDF (Cifrek et al., 2009; Dimitrova & Dimitrov, 2003). Simultaneous considerations of amplitude and MDF can provide information on whether EMG changes are fatigue-induced or force-induced. Cifrek et al. (2009) note:

> (1) If the EMG amplitude increases and the EMG spectrum shifts to the right, *muscle force increase* is the probable cause, (2) If the EMG amplitude decreases and the EMG spectrum shifts to the left, *muscle force decrease* is the probable

> cause, (3) If the EMG amplitude increases and EMG spectrum shifts to the left, this is considered to be the result of *muscle fatigue*, (4) If the EMG amplitude decreases and the EMG spectrum shifts to the right, this is considered to be *recovery from previous muscle fatigue.* (p. 332)

Currently, studies using EMG to assess the movements of softball players have focused on the upper body (Chang et al., 2010; Remaley et al., 2015; Rojas et al., 2009) or have detailed lower body activation in position-specific movements (e.g. catchers rising from a squat, the windmill pitch) (Oliver & Plummer, 2011; Plummer & Oliver, 2014). However, considering the kinetic chain and the importance of lower-limb applications of force (Suchomel et al., 2016), further investigations are needed to understand neuromuscular fatigue generated during softball-specific movements, such as batting.

2.5.2 Changes in Isometric Force

Most investigations of neuromuscular fatigue utilise isometric contractions during sub-maximal (Maton, 1981; McNeil et al., 2011; St Clair Gibson et al., 2001; Taylor & Gandevia, 2008) or maximal voluntary contractions (Bigland-Ritchie et al., 1983; Bigland-Ritchie et al., 1978; Bigland-Ritchie et al., 1992; Fauth et al., 2010; Rubinstein & Kamen, 2005; Taylor & Gandevia, 2008). Research demonstrates that fatigue first develops centrally during a maximal isometric contraction, then progresses to peripheral fatigue (Babault et al., 2006). Isometric contractions allow for the collection of stable EMG waveforms, limiting the spectral shift caused by factors unrelated to fatigue, such as a weakened signal due to a shift of the electrode from directly over the motor unit (Beck et al., 2014; Hägg, 1992). It is well established that EMG measurements during isometric contractions are reliable (Christ et al., 1994; Fauth et al., 2010; Kellis & Katis, 2008; Sleivert & Wenger; Viitasalo & Komi, 2008). Studies have also determined that isometric contractions exhibit a more significant leftward shift of an EMG signal's frequency content (i.e. evidence of developing neuromuscular fatigue) than from concentric or eccentric contractions (Kay et al., 2000). However, isometric contractions cause an accumulation of muscle metabolites due to ischemic conditions within the muscle during repeated isometric contractions (De Luca et al., 1983; Kay et al., 2000), potentially facilitating fatigue development. Researchers have also speculated whether isometric contractions provide a good representation of fatigue development during human movement due to the influence of contraction type, activity and duration on fatigue (Barry & Enoka, 2007; Enoka & Stuart, 1992;

Hunter et al., 2004; Kay et al., 2000). Despite these factors, the stability and quality of EMG data gathered during isometric contractions indicate its usefulness in measuring neuromuscular fatigue.

2.5.2.1 Force during Isometric Hip Adduction and Abduction

As the muscles of the hips and pelvis are responsible for the stability of the body during running and kicking movements, investigations regarding isometric hip strength in running-dominated sports like rugby, soccer and Australian football are prevalent (Buchheit et al., 2017; Crow et al., 2010; Fulcher et al., 2010; Roe, Phibbs, et al., 2016; Ryan et al., 2018; Thorborg et al., 2011; Wollin, Pizzari, et al., 2018). However, there is limited research on isometric hip strength in diamond-based sports. Inferences of changes in isometric strength from running-dominated sports cannot necessarily be applied to diamond-based sports as there is less continuous running and more intermittent gameplay in softball and baseball. A majority of power development in the kinetic chain occurs within the hips and pelvis, so understanding muscular strength changes in these regions is crucial to the performance and wellbeing of softball and baseball players.

At present, two studies have investigated changes in strength (measured by isometric force) of the hip musculature in softball players following a single game. Corben and colleagues (2015) evaluated bilateral hip strength of 19 female adolescent softball players (15.2 ± 1.2 years) before and after a single game pitching performance (5 ± 1 inning). Post-game fatigue was evident in all hip strength tests (hip adduction/abduction, flexion/extension), with a 19.3% and 15.2% reduction of strength in the dominant and non-dominant hips, respectively. Oliver et al. (2019) also measured isometric hip strength, range of motion, and vertical jump performance in five female collegiate softball pitchers and four collegiate softball catchers. In contrast to Corben et al. (2015), the authors detected limited reductions in isometric hip internal and external rotation of pitchers only (2.02% and 1.95%, respectively). Surprisingly, there were no significant losses in hip adduction/abduction strength for either pitchers or catchers.

Though research has not yet demonstrated evidence of force declines in hip adduction or abduction following a pitching performance in all age groups, one could speculate that adults may be more efficient in their movement patterns, producing less fatigue overall than the subjects used by Corben et al. (2015). Alternatively, adults may perform efforts at a greater intensity and decelerate greater magnitudes of momentum, generating greater fatigue than adolescent athletes. Age is a component of skills technique and injury prevalence in softball players; therefore, the generalisation of the findings from Corben et al. (2015) to highly experienced (>4 years of softball training at the state level or above) adult women is unknown. Such speculation emphasises the necessity of further research using adult softball players. Another limitation of the Corben et al. (2015) and Oliver, Plummer, et al. (2019) studies is that both delimited subjects to softball pitchers and catchers, with no assessment of changes in strength in other position players. Previous comparisons of hip strength between baseball position players and pitchers established that position players demonstrate significantly greater hip abduction strength than pitchers in the trail leg (i.e. leg on the same side as the throwing arm) (Laudner et al., 2010). The authors speculated that the difference in hip strength might relate to the addition of batting, of which pitchers in baseball and softball rarely participate. The authors also noted that the differences between pitchers and position players' hip strength might be due to the use of a pitching mound, which allows pitchers to use the downward slope to generate force towards home plate, while position players must generate force on level ground. While softball pitchers do not use a mound to pitch from, their throwing volume and throwing intensity is vastly higher than position players due to pitching demands and windmill pitching mechanics (Axe et al., 2002). However, changes in hip strength has not yet been compared between softball pitchers and position players. Additional research is needed to evaluate if changes in isometric hip strength occur in all softball positions, as the hip musculature is essential during rotatory actions prevalent in the sport.

2.5.2.2 Validity and Reliability of Isometric Upper Body Strength Measures

In addition to the importance of the hip musculature in softball athletes, evaluations of isometric strength changes within the upper body could be valuable for sport scientists and coaches when monitoring softball players. Mullaney et al. (2005) reported a strength loss of 18% during shoulder internal rotation in the throwing arm of collegiate baseball pitchers following a pitching performance (7 ± 2 innings). Skillington et al. (2017) also described significant reductions in shoulder strength (8.8 kg of force to 8.2, $p = 0.003$) in adolescent female softball pitchers throughout a weekend tournament. Conversely, no significant changes in strength were detected in shoulder internal and external rotation of collegiate softball pitchers and catchers after a single game (Oliver, Plummer, et al., 2019). Strength developed within the chest, shoulders, and arms supplement the power generated by the lower body during movements like throwing and batting (Kellett, 2017); thus, fatigue within the upper body of softball athletes may hinder performance outcomes such as batted ball or throwing velocity. Therefore, supplemental research of upper body isometric strength changes in softball players following single game and tournament play is necessary.

2.5.2.3 Reliability of Isometric Measures

As the measurement of adductor and abductor strength may be a practical measure capable of identifying the magnitude of neuromuscular fatigue in softball players, the reliability of the equipment used for these measures must be known. Isokinetic dynamometers are considered the gold standard for measuring isometric forces, but these devices are expensive and impractical for field-based use. Currently, handheld dynamometers (HHD) are a tool that many sport scientists use for testing isometric muscular strength in athletes due to the low cost of the devices and the ease of use in the field. Indeed, HHD were used in the two studies that focused on hip strength changes in softball players (Corben et al., 2015; Oliver, Plummer, et al., 2019). However, research has demonstrated that results from HHD may be influenced by administrator strength when providing an opposing force to the isometric movement (Wadsworth et al., 1992); lack of experience with the device (Wikholm & Bohannon, 1991); and the use, or lack of, stabilising equipment (Alfuth & Hahm, 2016; Jackson et al., 2017; Katoh, 2015).

The ForceFrame Hip Strength Testing System (Vald Performance, Albion, QLD) is a device intended for measuring isometric contractions of the hip and shoulders while eliminating the need for additional stabilisation or opposing forces applied by an administrator. It has previously demonstrated moderate to high reliability (ICC: 0.53 – 0.94) in male soccer and Australian Rules Football players when tested on a single day with multiple trials (Desmyttere et al., 2019; Ryan et al., 2018), acceptable reliability (ICC: 0.86 – 0.92) in female Australian Rules Football players when evaluated across multiple days (Kadlec et al., 2021), and a moderate to good correlation with HHD (r = 0.53 – 0.71) (O'Brien et al., 2019). However, it is imperative to determine the reliability of the ForceFrame in different populations, sports and within the upper- and lower-body, as well as determine how it compares to proven measures like the HHD.

2.5.2.4 Influence of Subject Positioning on Isometric Strength

At present, research has not standardised subject positioning when testing athletes' isometric strength. For example, of studies evaluating hip adduction strength, investigators have utilised hip and knee angles of 0° (Fulcher et al., 2010; Thorborg et al., 2011), 45° (Desmyttere et al., 2019; Fulcher et al., 2010; O'Brien et al., 2019; Roe, Darrall-Jones, et al., 2016), 60° (Kadlec et al., 2021; Ryan et al., 2018), or 90° (Buchheit et al., 2017; Fulcher et al., 2010). Delahunt and colleagues (2011) compared hip adductor muscle activity and strength production of male Gaelic games athletes when positioned at 0°, 45°, and 90° of hip and knee flexion and concluded that the most significant adductor muscle activity and strength values occurred at hip and knee angles of 45° (Delahunt et al., 2011). Similarly, Lovell et al. (2012) determined that hip adduction muscle activity was highest at 45° of hip and knee flexion; however, in contrast to Delahunt et al. (2011), the investigators determined that hips and knees positioned at 0° produced the greatest force output. Fulcher et al. (2010) also reported that handheld dynamometer intra- and interrater reliability was greatest when the subject was positioned with hip and knees angled at 90°, compared to 0° and 45°. Additionally, research does not have a consensus on the lever length when testing hip adductor strength. Two studies have concluded that the short lever positioning for testing (i.e. the force transducer is positioned between the medial condyles) produces a greater level of adductor EMG activity when compared to long lever testing positions (i.e. strain gauge is positioned at or just above the medial malleoli) (Delahunt et al., 2011; Lovell et al., 2012). Kadlec et al. (2019) reported a large relationship between short and long lever positioning when measuring adductor strength in male Rugby Union athletes, indicating similar strength results. However, one might suggest that isometric testing should occur in a position most similar to sport-specific movements. In softball players, a hip and knee angle of approximately 60° is typical in the ready position for fielding. Though this position may not elicit the same isometric strength values as other positions, the results gathered from testing softball players' in a sport-specific and oft-repeated position may be more informative of fatigue status and athlete readiness-to-play. Therefore, considerations for how the isometric strength values will be used (e.g. athlete monitoring, injury prevention or rehabilitation) and attention to the demands of the sport should dictate how subjects are positioned during isometric testing.

2.6 Playing Formats and Fatigue

As noted earlier, softball games are often played as part of a condensed tournament rather than throughout a long season. Prior research in softball and baseball has demonstrated that competitions played over several days causes a decrease in muscular strength (Skillington et al., 2017) and flight time: contraction time ratio (Nimphius, 2011a), a measure often used to indicate the presence of neuromuscular fatigue. Literature within other sports indicates that multi-day competitions cause an increase in muscle damage and joint stiffness (Clarke et al., 2015), a decrease in hitting accuracy (Gescheit et al., 2017), fewer repeated-sprint activities and an increased exercise-to-rest ratio (Spencer et al., 2005). It has also been established that neuromuscular function remains diminished 24 to 72 hours following competition (Cormack et al., 2008; Doeven et al., 2018; Houghton & Dawson, 2012; McLellan & Lovell, 2012; Roe, Phibbs, et al., 2016). Factors such as these highlight the importance of routine athlete monitoring during gameplay.

Unfortunately, neuromuscular decline is not limited to occurring only within competitive play. Research has also documented differences in workload and intensity encountered in training and competition (Cooke et al., 2019; Dawson et al., 2004; Ireland et al., 2019; Murphy et al., 2016; Petersen et al., 2011; Tallent et al., 2017). In a study of tennis's physical demands, investigators determined that training sessions were unlikely to adequately replicate competitive tournament demands (Murphy et al., 2016). In Australian Rules Football, the frequency of high intensity movements was much less in training than competition, providing longer recovery times than would regularly occur during competition (Dawson et al., 2004; Ireland et al., 2019). Simulated or skills-based training sessions for cricket players also did not match game demands, measured by mean heart rate and distance covered (Petersen et al., 2011). However, specific positions like fast bowlers regularly exceeded game demands during training, likely due to the requirement of both batting and bowling training (Cooke et al., 2019; Petersen et al., 2011; Tallent et al., 2017). To appropriately prescribe recovery from training or competition, coaches and sport scientists need to regularly assess their athletes' readiness. Future research involving softball athletes is necessary to establish neuromuscular declines caused by training sessions and competition.

2.7 Summary and Conclusion

The increase of softball's global popularity over the last 15 years prompts the necessity for further research to determine the sport-specific movement demands and the impact of neuromuscular fatigue on softball players during gameplay. Factors such as game durations of greater than two hours, the continuous anticipation and concentration during play, and the repetitive nature of frequent maximal-effort movements may exacerbate neuromuscular fatigue development. Therefore, it is first imperative to assess the movement demands of softball gameplay and then assess athletes' recovery from training or competition. Evaluations such as EMG analysis and measures of isometric force are practical methods of monitoring athletes' neuromuscular status and readiness-to-compete. However, further investigations are needed to apply these measures to softball players to determine the overall demands of a softball game and the impact of neuromuscular fatigue on softball players' muscular strength and performance.

At the request of the author,

Chapters 3 and 4 are unavailable in this version of the thesis

CHAPTER FIVE

Neuromuscular Fatigue Development in Female Softball Athletes during a Repetitive Batting Protocol

5.1 Introduction

Batting is a complex, highly coordinated multi-joint movement that requires precise timing and accuracy, and is considered one of the most challenging skills to develop in sports (Mihoces, 2003; Reilly-Boccia et al., 2015; Williams & Underwood, 1986). The development and transfer of momentum from the lower extremities to the upper extremities through proximal-to-distal sequencing is vital to the power generation of the bat swing. The batter must maintain stability in the hips and pelvis throughout the movement to minimise loss of force during the transfer from the lower to the upper body (Washington, 2018). Because batting is the primary offensive movement in softball, disruptions within the kinetic chain caused by fatigue may directly impact the success of the individual athlete and the team.

Bat swings occur approximately 17 times per game for individual softball players (Cardwell, 2021). However, this value does not account for pre-game batting practices, which may double, or even triple, bat swing frequency. Further, most bat swings performed in game are taken with the intent to drive the ball to the outfield, requiring maximal power generation and bat speed. At present, only one study has investigated the effect of fatigue caused by batting. Bounds (2010) evaluated a functional fatigue protocol specific to batting, with collegiate softball players completing 100 maximal bat swings for contact at a rate of one swing every three seconds. In their report, significant decreases in bat swing velocity (6.8%) and batted ball velocity (6.1%) were detected (Bounds, 2010). Previous research has determined that higher bat swing velocity is associated with increased time for decision, decreased swing time, and increased batted ball velocity (DeRenne et al., 1995; Reyes & Dolny, 2009; Szymanski et al., 2009). Consequentially, the effect of fatigue could significantly impact the offensive success of softball batters. As lower body power plays a significant role in bat swing velocity (Hoffman et al., 2009; Miller & Bemben, 2017; Szymanski et al., 2009; Till et al., 2011), it is necessary to evaluate the level of neuromuscular fatigue and its impact on hip musculature when batting.

Many investigations of neuromuscular fatigue utilise isometric contractions during maximal voluntary contractions (Bigland-Ritchie et al., 1983; Bigland-Ritchie et al., 1978; Bigland-Ritchie et al., 1992; Fauth et al., 2010; Rubinstein & Kamen, 2005; Taylor & Gandevia, 2008). Isometric hip strength has been used to assess neuromuscular status of baseball and softball pitchers (Corben et al., 2015; Mullaney et al., 2005; Oliver, Plummer, et al., 2019); however, these variables have not been evaluated in response to potential batting induced fatigue. While the information on the neuromuscular status of pitchers is useful in understanding the effects of repetitive movement in maintaining movement efficiency, these data cannot be applied in a practical way to batters due to differences in movement and frequency. The primary lower body movements of pitching rely heavily upon hip flexion while batters utilise axial rotation (Campbell et al., 2010; Welch et al., 1995). Further, pitchers pitch approximately 112 times throughout a seven inning game, compared to batters who may take 17 bat swings in the same time frame (Cardwell, 2021). As a result, changes in isometric strength that occur in batters and pitchers are likely very different; therefore, additional research is needed to evaluate reductions in isometric hip strength in response to batting.

Although measures of isometric strength provide an evaluation of neuromuscular status in large muscle groups, EMG allows for a more detailed estimation of neuromuscular changes occurring within individual muscles. It is possible to evaluate changes in motor unit recruitment and rate coding of isolated muscles through the use of amplitude and frequency of the EMG waveforms during isometric contractions (Konrad, 2005). At present, studies have primarily used EMG to assess upper body movements of softball players (Chang et al., 2010; Remaley et al., 2015; Rojas et al., 2009) or to detail lower body activation in position-specific movements (e.g. catchers rising from a squat, the windmill pitch) (Oliver & Plummer, 2011; Plummer & Oliver, 2014). Though the results of these investigations contribute to a better understanding of movements found in softball, there is still an absence of information regarding EMG changes in the hip musculature of softball players as a result of batting.

Finally, changes in performance variables are often used as indicators of neuromuscular fatigue. Elite athletes' ability to adapt to changing task requirements allows for movement variability, or the normal variations in motor performance across multiple repetitions of a task (Stergiou & Decker, 2011). Despite their best efforts, however, elite athletes are not immune to the effects of neuromuscular fatigue, which may manifest as pattern changes in muscle activity, increased modulations of isometric force, and alterations in movement dynamics (Cortes et al., 2014). As a result, variability within the performance outcomes (i.e. changes in batted ball velocity) may provide meaningful indicators of fatigue development. Similar to the results of the study by Bounds (2010), other investigations using baseball players have also described reductions in running and throwing velocity, throwing accuracy, and compromised neuromuscular control as a result of fatigue (Escamilla et al., 2007; Freeston et al., 2014; Murray et al., 2001; Tripp et al., 2007). As softball games are often played within a condensed tournament schedule and softball players routinely participate in multiple games per day, regular assessment of performance variables should be implemented to prevent injury or overuse. However, research must first detail how performance variables change with exposure to repeated bat swings.

Considering the kinetic chain and the importance of lower-limb applications of force (Suchomel et al., 2016) in common movements of softball play (e.g. batting, throwing, jumping), further investigations are needed to determine the effects of neuromuscular fatigue from repeated bat swings on muscle strength, muscle activity, and performance variables in softball players. The current study aims to 1) assess neuromuscular fatigue development measured by isometric force and EMG in hip strength assessments of female softball players intermittently during a repeated batting protocol and 2) evaluate changes in performance variables (e.g. batted ball velocity, RPE) caused by fatigue.

5.2 Methods

5.2.1 Experimental Approach to the Problem

Our aim was to examine changes in isometric force, electromyographic activity, batted ball velocity, and perceived exertion before, during and after completing a fatiguing batting protocol. The methodology for this study was designed to induce a fatigued state rather than replicate match play conditions. Thus, the protocol was completed in a controlled environment rather than on a playing field. The protocol alternated single trials of maximal voluntary isometric contractions in hip adduction and abduction with sets of 10 batted balls off a batting tee, with the subject completing nine rounds of isometric contractions and 80 bat swings in total. Though results in Chapter 3 indicate a softball players takes approximately 17 bat swings throughout a game (Cardwell, 2021), a total of 80 bat swings was chosen to magnify any fatigue development that occurred within the subjects. Bilateral isometric force and measures of sEMG median frequency and amplitude of the adductor longus (AL), tensor fascia latae (TFL), and gluteus medius (GM) muscles were assessed during isometric contractions. Batted ball velocity was determined for each hit using a calibrated radar gun and averaged across a single round. Exercise intensity, measured by the Borg Rating of Perceived Exertion (RPE) scale, was evaluated after each round of isometric contractions.

5.2.2 Subjects

Due to constraints caused by COVID-19 during data collection, subject participation was limited, and the study did not achieve statistical power. Four female softball players participated in this study, and their results are presented as individual case studies. The subjects were assessed for within-subject changes as a result of neuromuscular fatigue. Table 8 presents demographic data for each subject. The Human Research Ethics Committee approved the research protocol (Approval #21828). Subjects provided written and informed consent before starting the study.

Table 1. Demographic data of all subjects.

	Age	Body mass	Height	Bats/ Throws	Level of Softball Experience	Actively Training or Competing?
Subject 1	25 yrs	83.5 kg	1.77 m	R/R	11 yrs, State and National teams	Not active
Subject 2	18 yrs	65 kg	1.67 m	R/R	12 yrs, State and Junior National teams	Off-season softball
Subject 3	23 yrs	62.0 kg	1.66 m	L/R	10 yrs, State and National teams	Not active
Subject 4	20 yrs	65.7 kg	1.63 m	L/R	5 yrs, State team	Australian Rules Football

Right-handed, R; Left-handed, L.

5.2.3 Procedures

Testing was completed in a laboratory setting with temperature control. Height was measured to the nearest 0.1 cm with subjects standing barefoot on a stadiometer. Weight was measured to the nearest 0.1 kg with subjects in exercises attire without shoes on an electronic scale (A&D Electronic Scale, UC-321). A Wave Wireless EMG (Cometa Systems, Bareggio, IT) system recorded EMG signals, sampling at 2000 Hz. Surface electrodes (Ag-AgCl, inter-electrode distance of 2 cm) were placed bilaterally over the muscle bellies of the AL, TFL, and GM of the subject. Electrode location was determined by manual palpation and previously established guidelines (Cram, 2011) (Figure 9).

At the request of the author,

this image is unavailable in this version of the thesis

Figure 2. The location of surface electrodes over the adductor longus (a), tensor fascia latae (b), and gluteus medius (c) (Cram, 2011).

Before electrode placement, the skin was carefully shaved and abraded to keep inter-electrode resistance below 5 kΩ. EMG data was measured on the front and back legs. For a right-handed batter, the front leg is the left leg, which receives loading following bodyweight shift during swing initiation. The back, or right leg, is responsible for power generation during the swing. These designations are reversed for left-handed batters. Figure 10 illustrates the responsibilities of each leg during a bat swing.

At the request of the author,

this image is unavailable in this version of the thesis

Figure 3. In batting, power generation develops in the back leg. The front leg receives loading following a bodyweight shift during swing initiation. Credit to Paige Sandvik for illustration.

Following electrode placement, the subject performed a standardised dynamic warm-up (Appendix B), followed by 2 min of non-contact bat drills and five submaximal effort bat swings for contact. The subject was allowed to use their own softball bats and set the batting tee height to their preference.

5.2.4 Batting and Testing Protocol

Figure 11 is a visual depiction of the overall protocol. The protocol began with the Pre-test, involving a single 5 s MVIC for both hip adduction and abduction, with 10 seconds between each contraction. EMG data and isometric force were collected during all isometric contractions, and the subject was asked for their RPE score immediately following the final MVIC. Following a two-minute rest period, the subject began the first batting set, comprising of ten batted balls from a tee, paced every 10 s by a stopwatch. Though previous research has indicated some kinematic differences when batting off a tee versus using a front toss method of batting (Washington & Oliver, 2018) and front toss may be more similar to a game setting, the use of the tee was selected for ability to replicate hitting conditions on each swing, as well as being a commonly used tool in training sessions. The subject was instructed to hit the ball as hard as they could. Subject 3 and 4 were primarily slap hitters (a hitting style used by left-handed batters who take a running start before hitting the ball) (Chang et al., 2011; Washington, 2018), but they batted stationary for the study. Subjects 1 and 2 were right-handed batters and, therefore, always batted stationary. Batted ball velocity was recorded for each hit. After the tenth batted ball of the set, the subject undertook the testing protocol, which consisted of a single 5 s MVIC for each hip adduction. After a 10 s recovery period, the subject performed a single five-second MVIC for hip abduction. Force and EMG data were collected during each MVIC. RPE scores were recorded after completing both MVICs, with the score encompassing total exercise intensity felt thus far. After a 2 min rest period, the subject returned to the batting tee and began another round of batting. They completed eight sets of batting (i.e. ten swings per set), with the testing protocol and then 2 min rest between each set and after the final set. Hence, a total of 80 batted balls and nine sets of MVICs were completed throughout the entire batting protocol.

Other measures taken during testing were batted ball velocity, isometric hip strength, and exercise intensity. A calibrated radar gun (Stalker Radar, Richardson, TX, USA) measured each trial's batted ball velocity (BBV). The radar gun was held at chest height behind the batting net to record ball speed off the bat. Isometric hip strength was measured immediately following each batting set. The ForceFrame Strength Testing System (ForceFrame) (Vald Performance, Albion, QLD) measured isometric hip adductor and abductor strength by undertaking a maximal voluntary isometric contraction (MVIC). The subject was instructed to lie supine with hips and knees bent at 60° of flexion determined by a digital goniometer (Digital Protractor

Goniometer, Medigauge, Columbia, MO) (Ryan et al., 2018). The crossbar height was adjusted so that hips and knees remained at 60° and the force transducers were in contact with the medial femoral condyle during adduction and lateral femoral condyle during hip abduction. Prior to testing, the subject was given instruction and allowed up to five submaximal trials for familiarisation with the ForceFrame. For each movement, the subject was instructed to push with maximal effort for five seconds, and the peak isometric force of each leg was recorded. This measurement occurred before the commencement and after the conclusion of each batting set. The Borg Rating of Perceived Exertion (RPE) 6-20 scale (Borg, 1982) was used to estimate exercise intensity. Explanation of the scale occurred before testing began, and subject RPE scores were estimated following after each round of isometric measures. A copy of the scale was on hand for subject reference during the protocol.

5.2.5 Data Analysis

Limited subject recruitment (due to COVID-19 interruptions) lead to a case study approach and intra-subject differences were qualitatively assessed. Variables determined were median frequency (MDF), maximum EMG amplitude, BBV, peak isometric force, and RPE.
All raw EMG signals were Bandpass filtered at 6-500 Hz. Filtered EMG signals were checked visually to ensure correct signal acquisition. For each individual muscle, median frequency of the filtered EMG signal was calculated from the power density spectrum of the middle three seconds of a five-second contraction of each MVIC during each trial, discarding the first and last second. Processing of the EMG amplitude data was performed by using a root mean square (RMS) with a window of 100 ms to smooth the data for each muscle during each MVIC. The maximal value (amplitude) was identified over the middle three seconds of the five-second MVIC, discarding the first and last second. Amplitude was then normalised to subject's Pre-test values of hip adduction and hip abduction and presented as Normalised Peak EMG (%).

Isometric force data was also normalised to the subject's Pre-test values and presented as Normalised Isometric Force (measured in newtons [N]). Mean and standard deviations of BBV were calculated using the ten batted balls in each set.

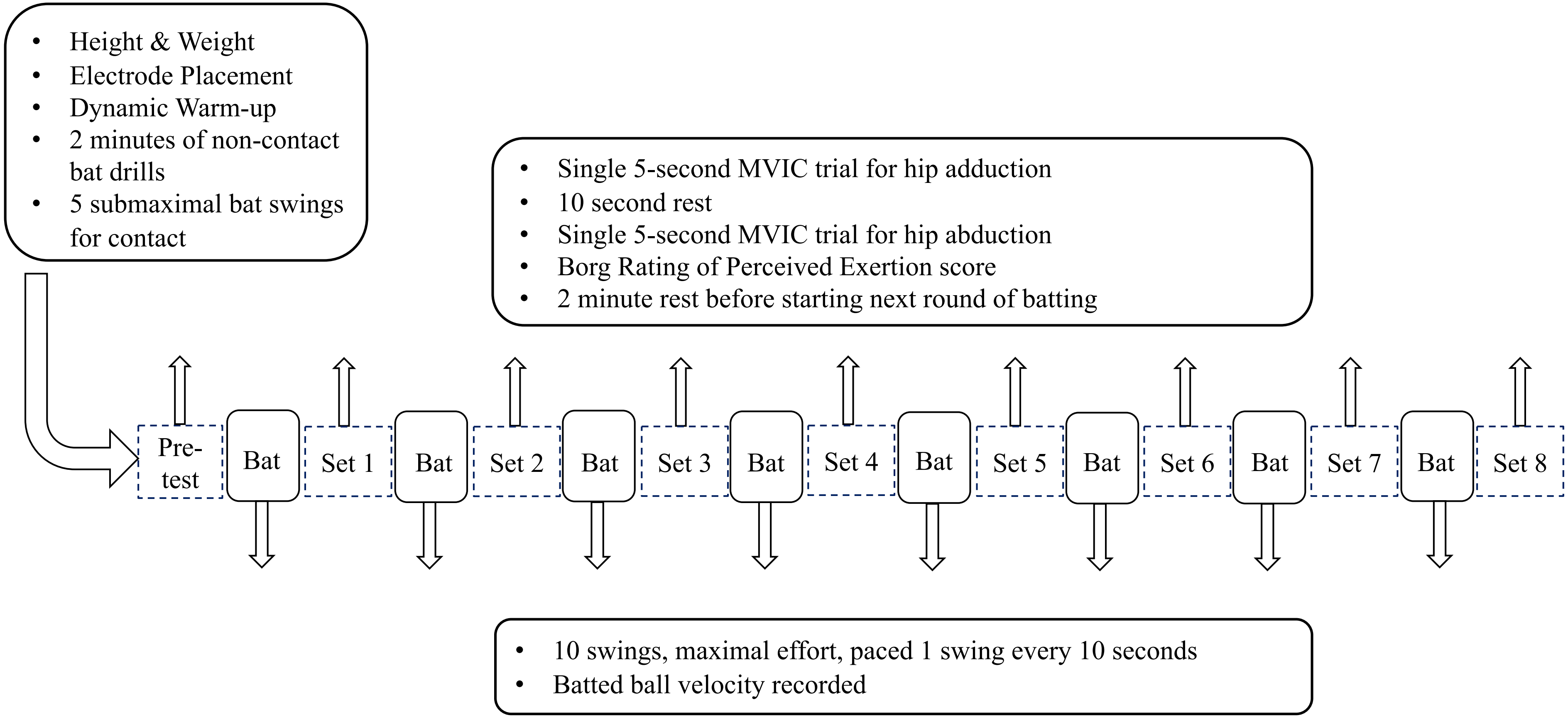


Figure 4. A visual representation of the batting protocol. MVIC = Maximal voluntary isometric contraction.

5.3 Results

5.3.1 Subject 1

Subject 1 demonstrated an initial increase then shift towards lower frequencies for MDF across all sets during hip adduction (Figure 12). During hip abduction, all front leg muscles and the back AL exhibited an initial increase toward higher frequencies before shifting to lower frequencies (Figures 13a-c, e). However, following an initial increase, the back leg TFL and GM muscles' MDF remained similar to Pre-test frequencies throughout the batting protocol (Figures 13d, f). Increases in normalised amplitude of the EMG during hip adduction were displayed in Subject 1's front leg GM and back leg AL (Figures 14a and 14b, respectively). Normalised amplitude of the EMG increased across all muscles in both legs during hip abduction (Figures 14c and 14d).

During hip adduction, force increased from Set 1 to Set 4 in all muscles, then declined until the end of the protocol (Figure 15a). Batted ball velocity (also displayed in Figure 15a) was consistent throughout all sets, though displayed large standard deviations in Sets 2, 6 and 8 (±9.2 km.h^{-1}, ±13.5 km.h^{-1}, and ±11.5 km.h^{-1}, respectively). Force increased in both legs from Pre-test levels during hip abduction during all sets except for Set 2 and 6 (Figure 15b). Borg RPE scores increased from 16 to 19 from Sets 1-6 but decreased to 17 for the final two sets (Figure 15b).

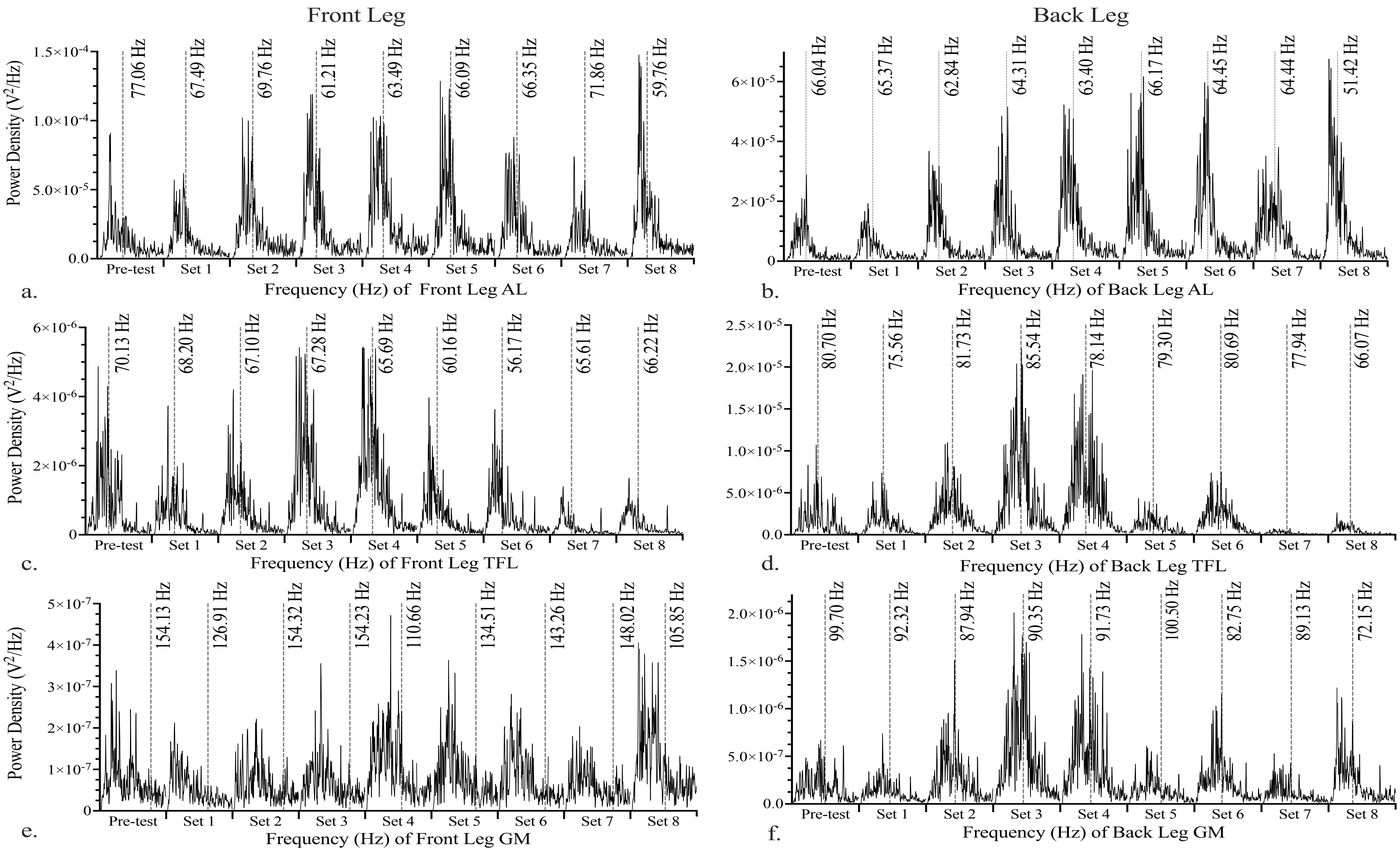


Figure 5. A power spectral density (PSD) of filtered EMG signals from the front and back leg adductor longus muscles (a and b), tensor fascia latae (c and d), and gluteus medius (e and f) muscles of Subject 1 during adduction. Median frequencies are demonstrated by dashed lines. Each set is presented over a 200 Hz axis.

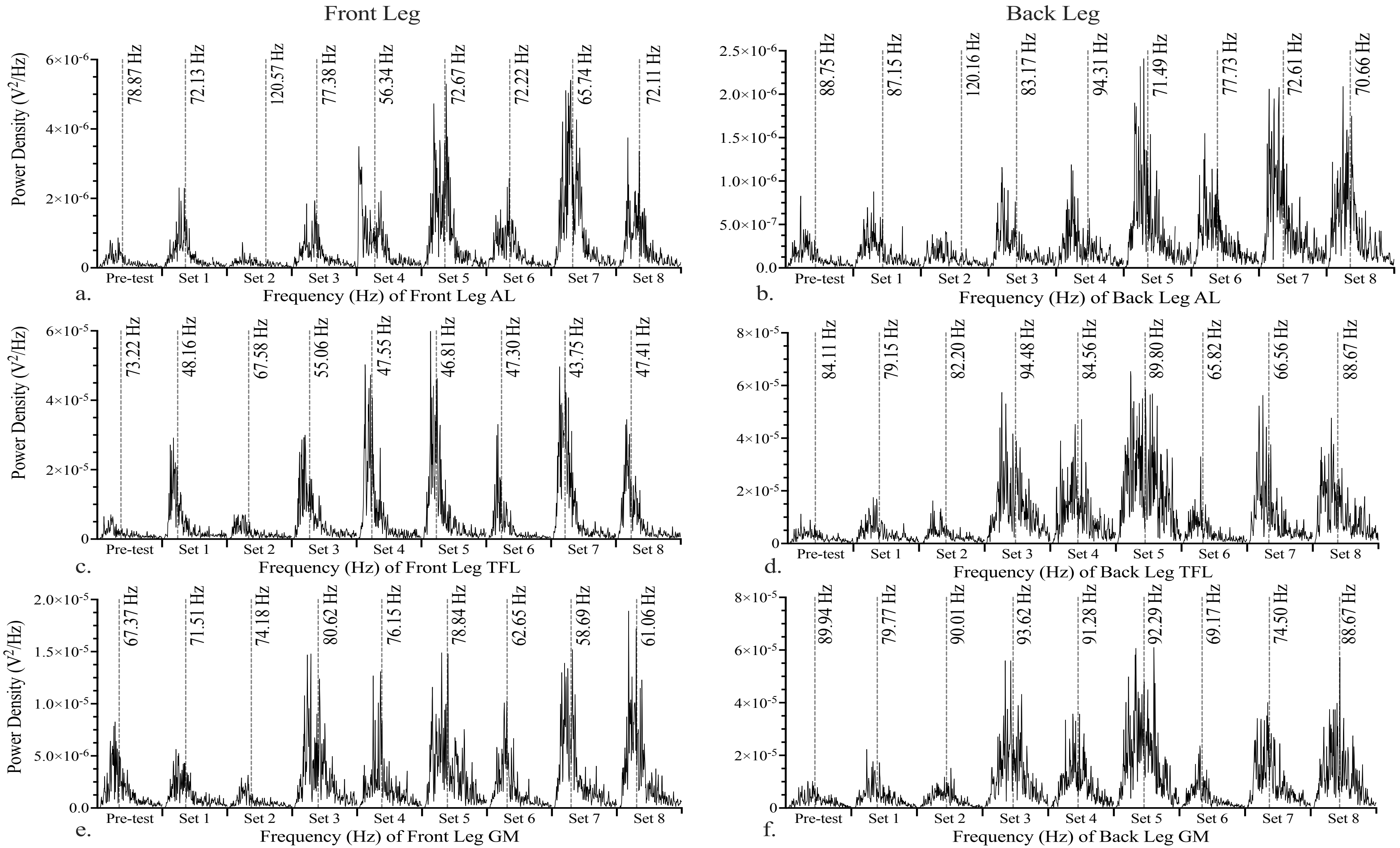


Figure 6. A power spectral density (PSD) of raw EMG signals from the front and back leg adductor longus muscles (a and b), tensor fascia latae (c and d), and gluteus medius (e and f) muscles of Subject 1 during abduction. Median frequencies are demonstrated by dashed lines. Each set is presented over a 200 Hz axis.

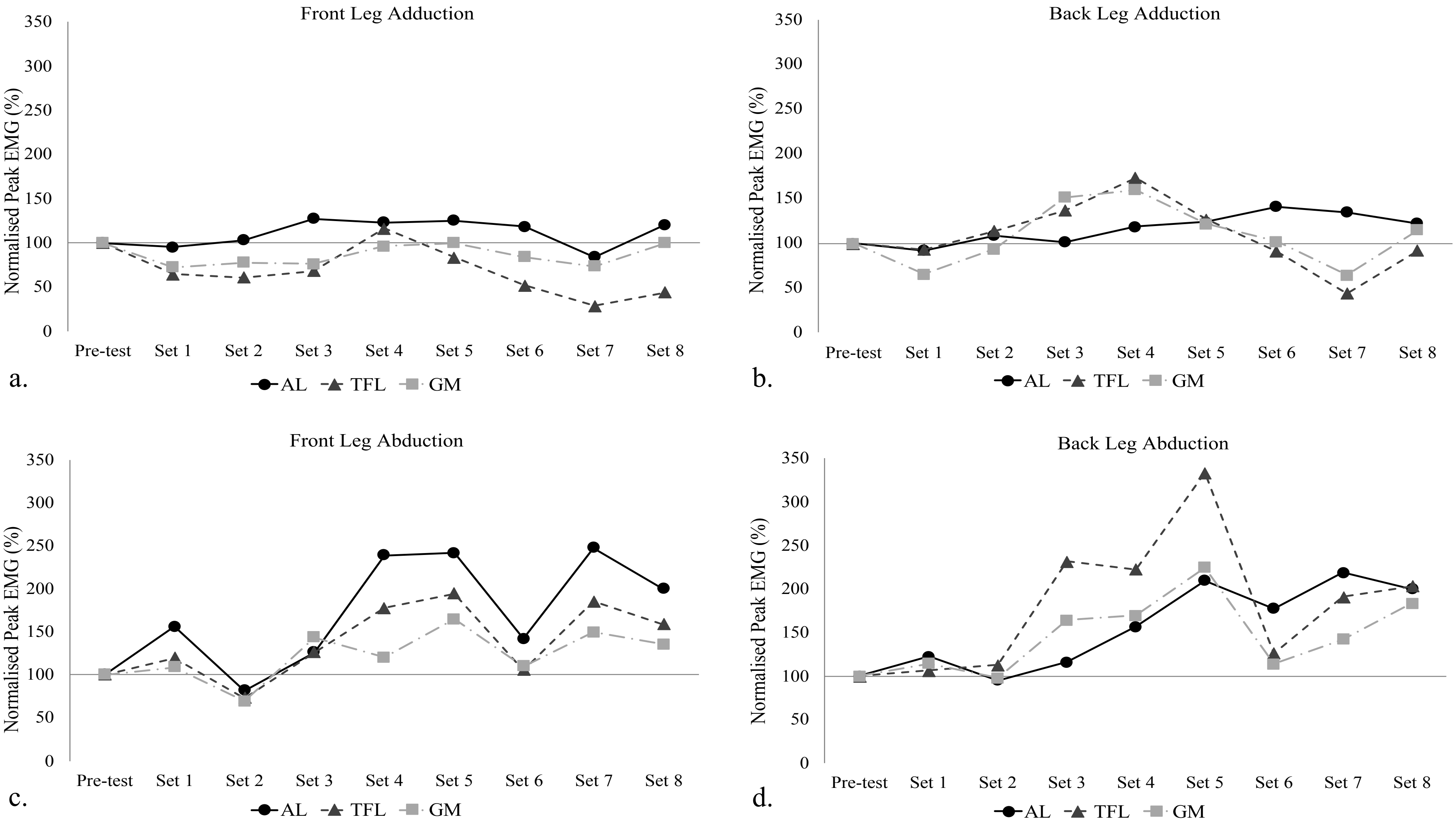
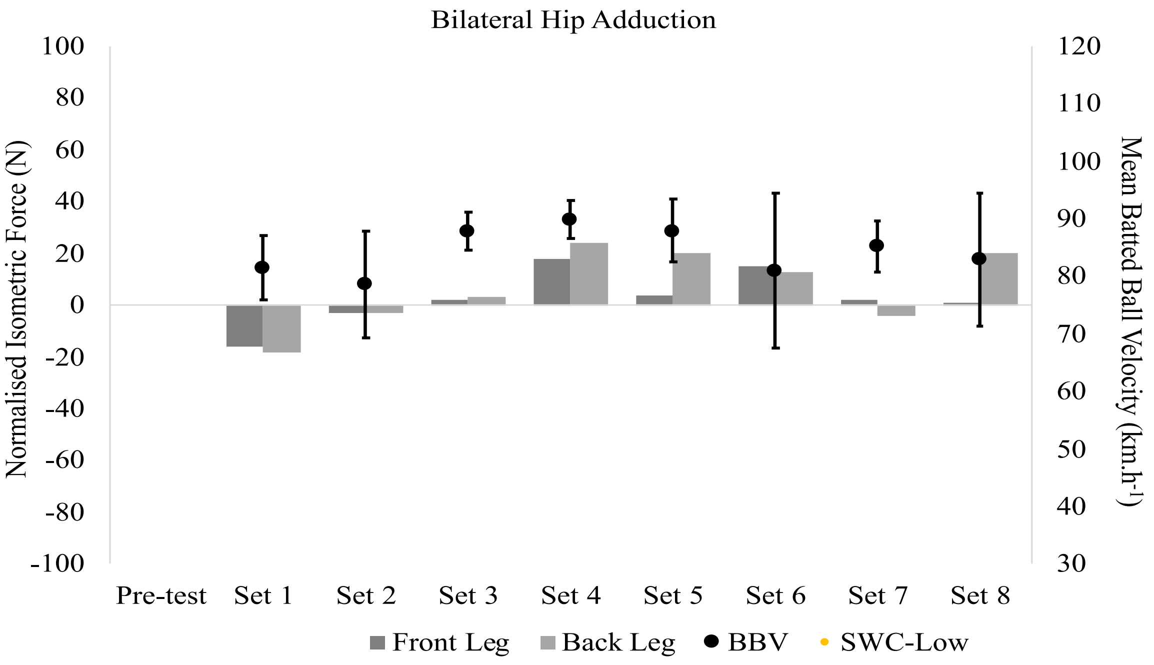
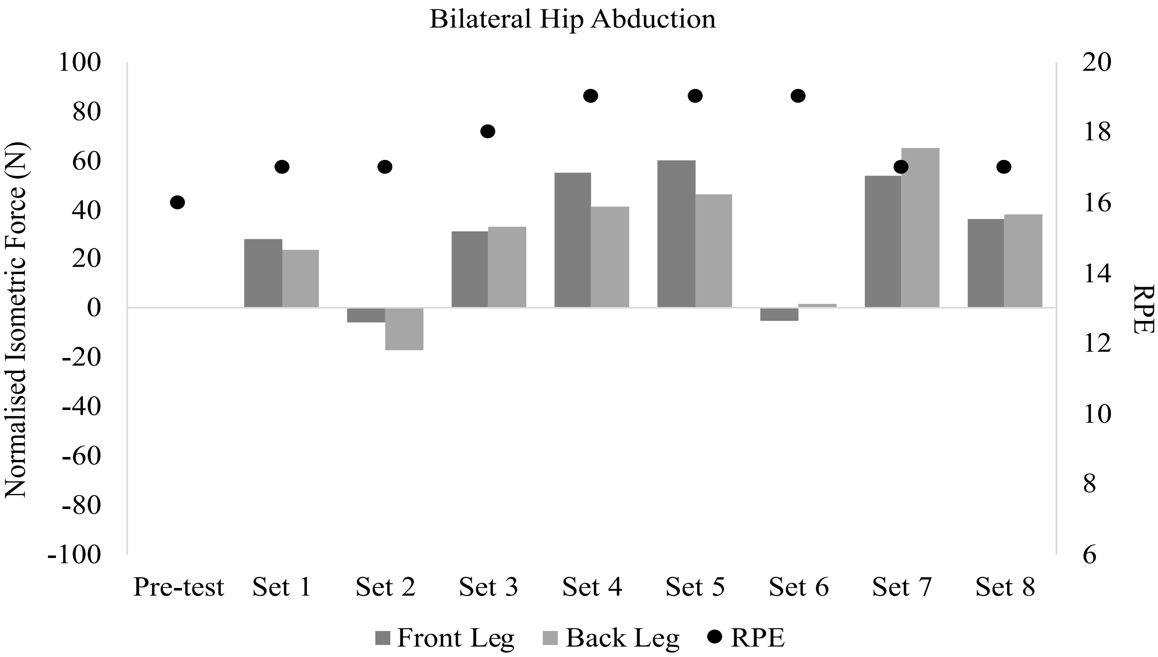


Figure 7. EMG amplitude of Subject 1 during hip adduction (front leg, a; back leg, b) and abduction (front leg, c; back leg, d). Amplitude was normalised to Pre-test amplitude. An increase in amplitude is indicative of increased recruitment of additional motor units. AL: Adductor Longus; TFL: Tensor Fascia Latae; GM: Gluteus Medius.



a.



b.

Figure 8. a) Bilateral isometric hip adduction force for Subject 1 normalised to Pre-test values, overlaid with mean batted ball velocities of each set. Error bars denote standard deviations. b) The bilateral isometric hip abduction force of Subject 1 normalised to Pre-test values. Overlaid values are Borg RPE scores reported after each set.

5.3.2 Subject 2

Due to electrode failure, data for the GM of Subject 2 was only collected through to the end of Set 3 for the front GM and through to the end of Set 7 on the back GM. During hip adduction, the front AL and back TFL muscles exhibited increases in MDF throughout the entire protocol (Figures 16a, d). MDF shifted to lower frequencies in the front TFL and back GM muscles during hip adduction after initial increases, but were steady in the front GM and back AL muscles following initial rises (Figures 16b, c, e-f). Front and back AL muscles during abduction remained uniform following small initial rises, with cumulative decreases indicated in the front and back TFL and GM muscles (Figure 17). Though variabilities in normalised EMG amplitude were present during adduction in the front AL, front TFL, and the back GM, no clear trend towards fatigue appears (Figures 18a and b). Similarly, no clear indication of movement toward higher normalised amplitudes emerges in any muscles during abduction (Figures 18c and d).

Isometric force during adduction oscillated in both legs, with declines over Sets 1-3 and 5-6 and increased force during Sets 4, 7 and 8 (Figure 19a). Batted ball velocity was stable during first four sets, then declined to finish 10 km.h^{-1} less than earlier sets; while standard deviations stayed below ±10 km.h^{-1} during all sets (Figure 19a). Like adduction, isometric force fluctuated throughout all sets, increasing bilateral force during the final four sets (Figure 19b). RPE score increased from 10 at Pre-test to 13 by the end of the protocol.

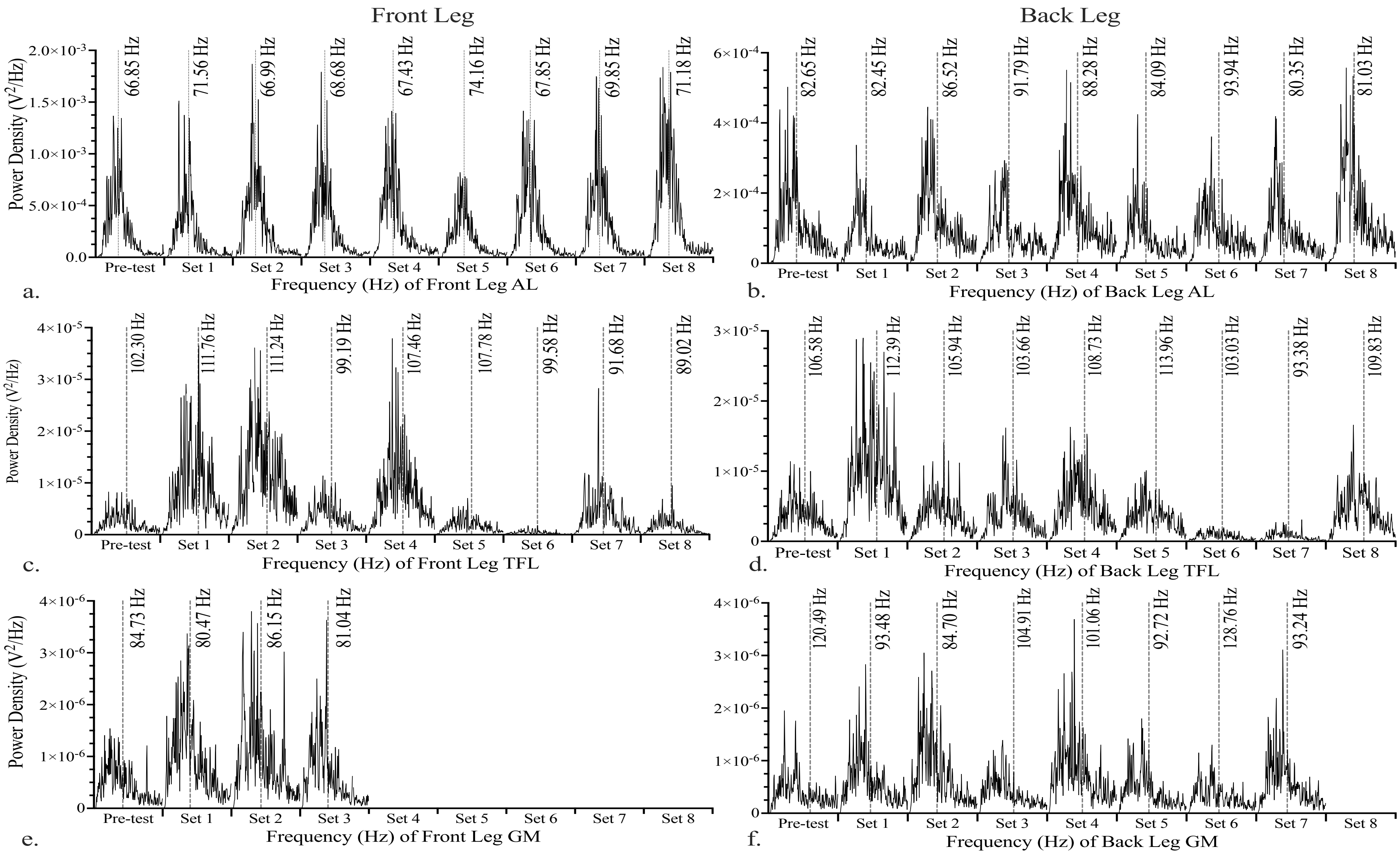


Figure 9. A power spectral density (PSD) of raw EMG signals from the front and back leg adductor longus muscle (a and b), tensor fascia latae (c and d), and front gluteus medius (e) muscles of Subject 2 during adduction. Median frequencies are demonstrated by dashed lines. Each set is presented across a 200 Hz axis. No front leg gluteus medius signal was recorded during sets 4-8 due to electrode error. No back leg gluteus medius signal was recorded during set 8 due to electrode error.

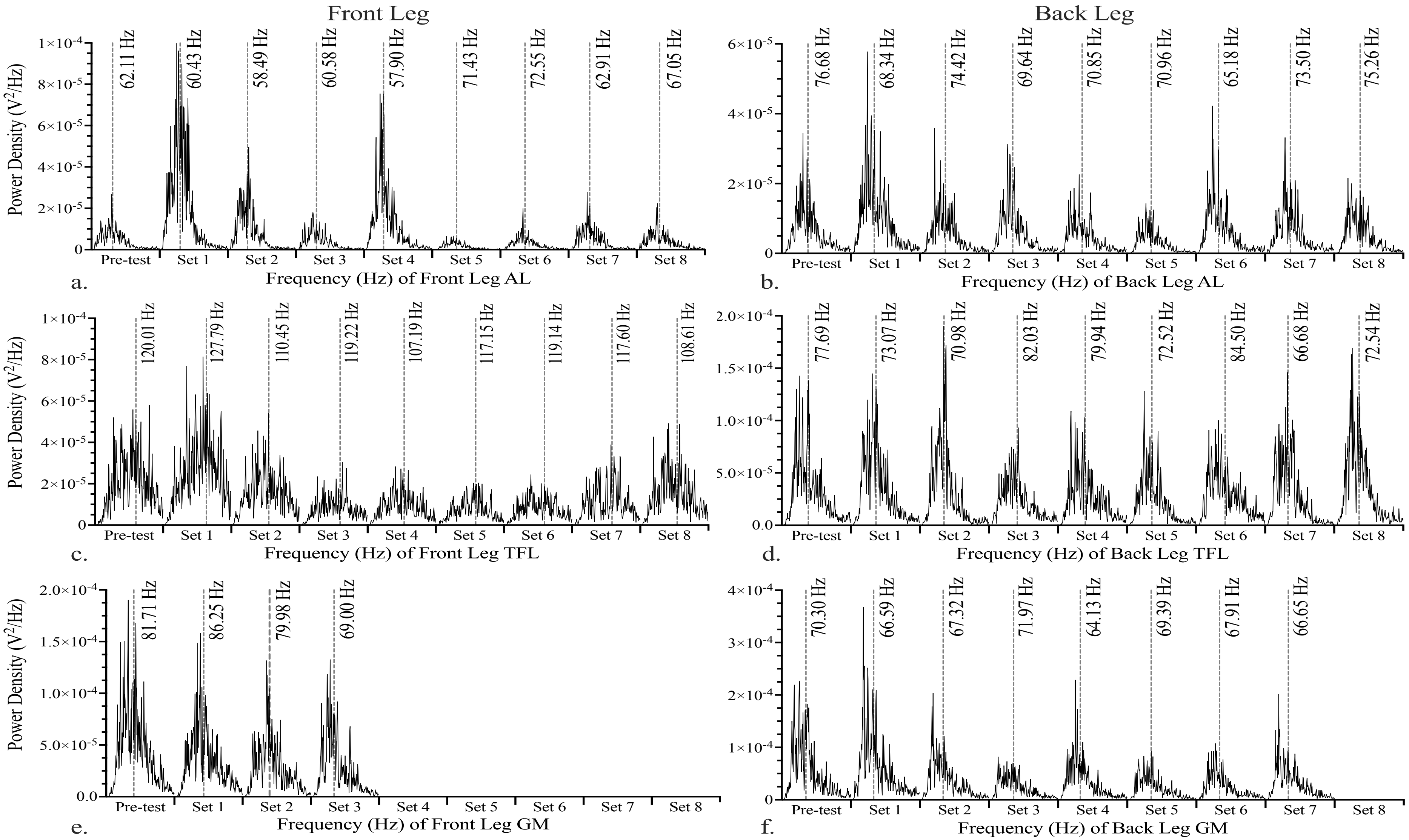


Figure 10. A power spectral density (PSD) of raw EMG signals from the front and back leg adductor longus muscle (a and b), tensor fascia latae (c and d), and front gluteus medius (e) muscles of Subject 2 during abduction. Median frequencies are demonstrated by dashed lines. Each set is presented across a 200 Hz axis. No front leg gluteus medius signal was recorded during sets 4-8 due to electrode error. No back leg gluteus medius signal was recorded during set 8 due to electrode error.

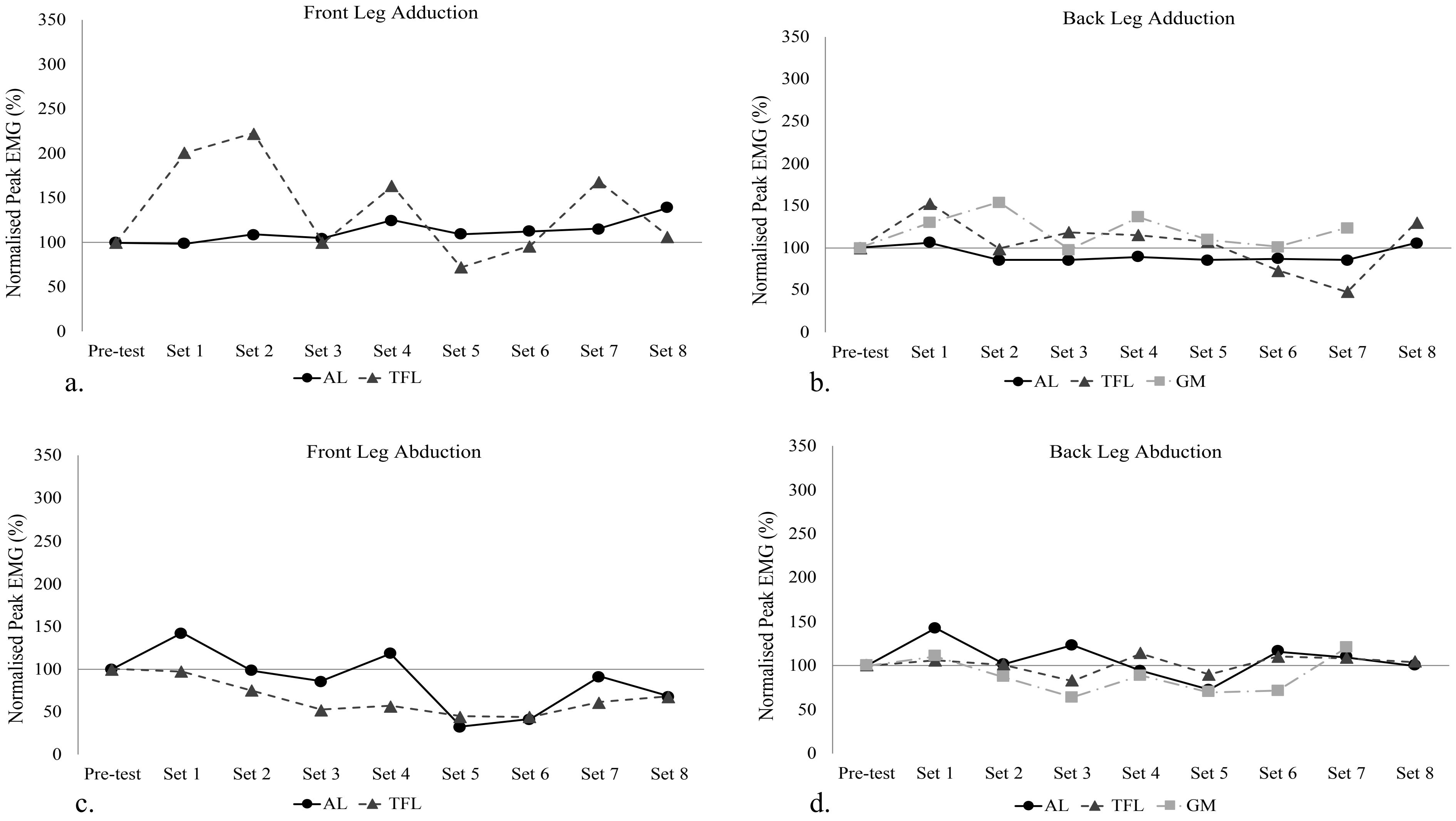
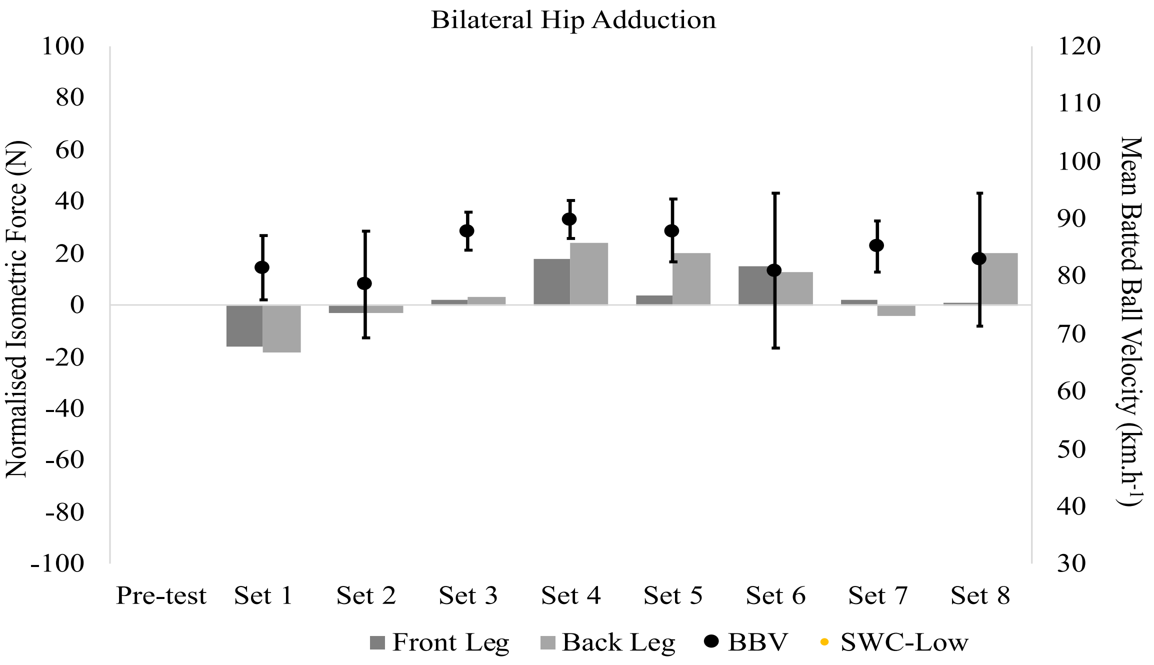
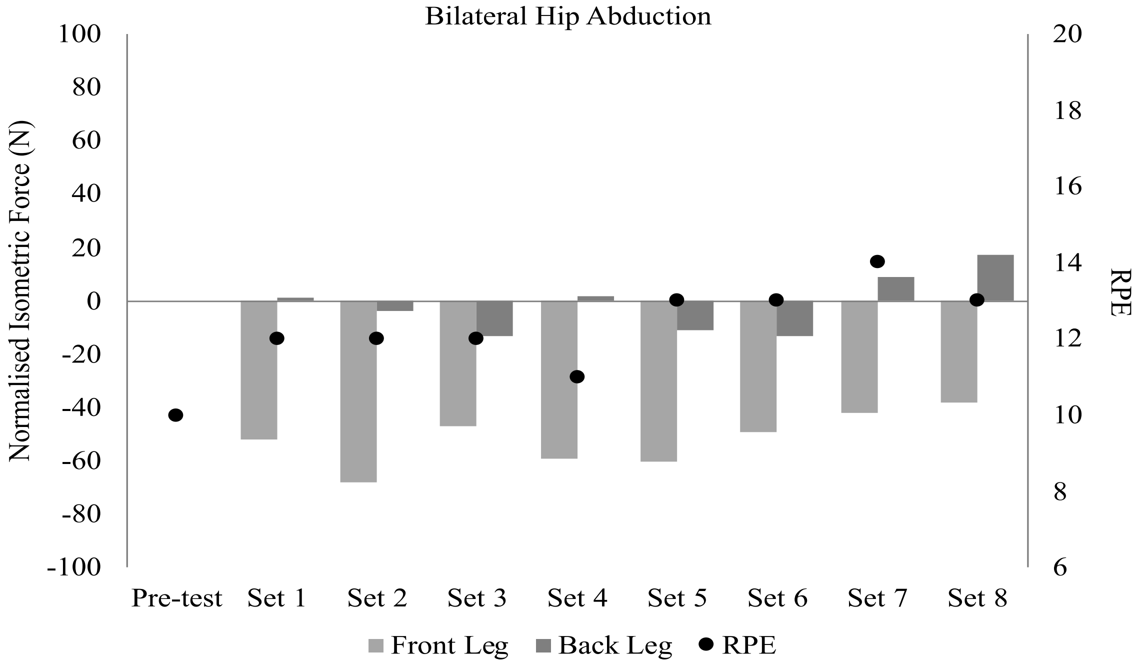


Figure 11. EMG amplitude of Subject 2 during hip adduction (front leg, a; back leg, b) and abduction (front leg, c; back leg, d). Amplitude was normalised to Pre-test amplitude. No front leg gluteus medias data was recorded during sets 4-8 due to electrode error. No back leg gluteus medius signal was recorded during set 8 due to electrode error. An increase in amplitude is indicative of increased recruitment of additional motor units. AL: Adductor Longus; TFL: Tensor Fascia Latae; GM: Gluteus Medius.



a.



b.

Figure 12. a) Bilateral isometric hip adduction force for Subject 2 normalised to Pre-test values, overlaid with mean batted ball velocities of each set. Error bars denote standard deviations. b) The bilateral isometric hip abduction force of Subject 2 normalised to Pre-test values. Overlaid values are Borg RPE scores reported after each set.

5.3.3 Subject 3

Due to electrode error, no analysis was available for the back leg GM muscle of Subject 3. After an early rise in frequency in the early sets, the MDF of Subject 3 was consistent throughout all sets of hip adduction in the front and back leg AL muscles (Figures 20a and 20b); however, shifts to lower frequencies following early rises were present in both TFL muscles and the front GM muscle (Figures 20c-e). During hip abduction, the front and back AL, front TFL and front GM muscles demonstrated initial increases in frequency, then remained steady through the rest of the protocol (Figure 21a-c, e). The back TFL muscle increased in median frequency during hip abduction throughout the protocol (Figure 21d). Similarly, normalised amplitude of the EMG of all muscles during hip adduction was inconsistent with evidence of increased recruitment (Figures 22a and 22b). However, during hip abduction, both TFL muscles and the front AL muscle increased in normalised EMG amplitude (Figures 22c, 22d).

Back leg force production decreased from Set 1 to Set 6 during adduction, then gained strength for the final two sets (Figure 23a). Despite an initial increase of 55 N in the front leg from Pre-test to Set 1, the front leg also displayed a decrease in force production through set 6, then increased again for the final two sets (23a). Batted ball velocity also remained consistent throughout all sets, though large standard deviations developed in sets 4-6 (±11.9 km.h^{-1}, ±13.0 km.h^{-1}, and ±15.3 km.h^{-1}) (Figure 23a). Force production was more evenly distributed between the front and back legs during hip abduction, leading to similar increases in force from Pre-test to Set 2, a subsequent decline until Set 6, and a final increase in force for the final two sets (Figure 23b). Borg RPE scores increased throughout the protocol, rising from 6 at Pre-test to 10 at Set 8 (23b).

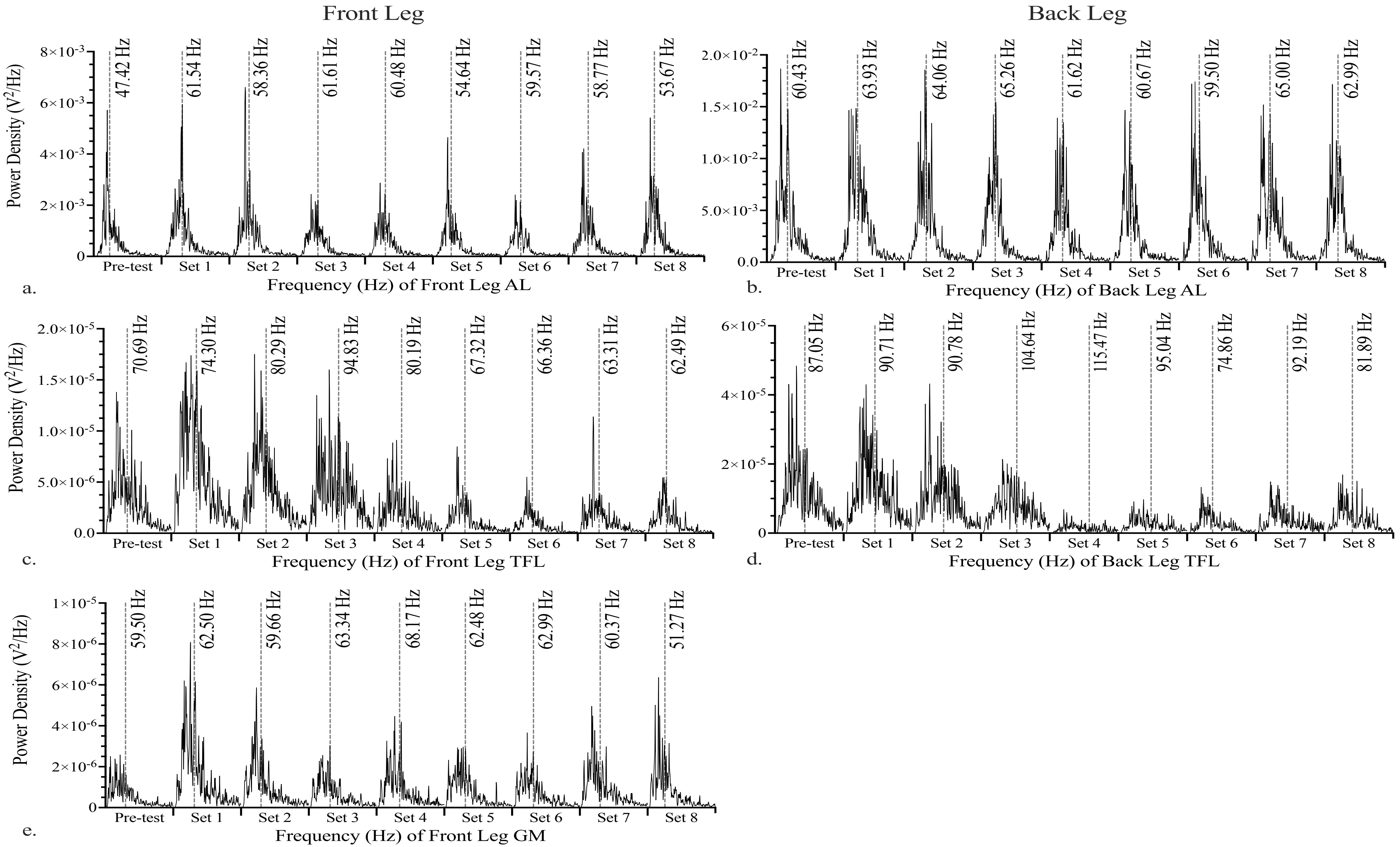


Figure 13. A power spectral density (PSD) of raw EMG signals from the front and back leg adductor longus muscle (a and b), front tensor fascia latae (c), and front and back gluteus medius (d and e) muscles of Subject 3 during adduction. Median frequencies are demonstrated by dashed lines. Each set is presented across a 200 Hz axis. No back leg gluteus medius signal was recorded due to electrode error.

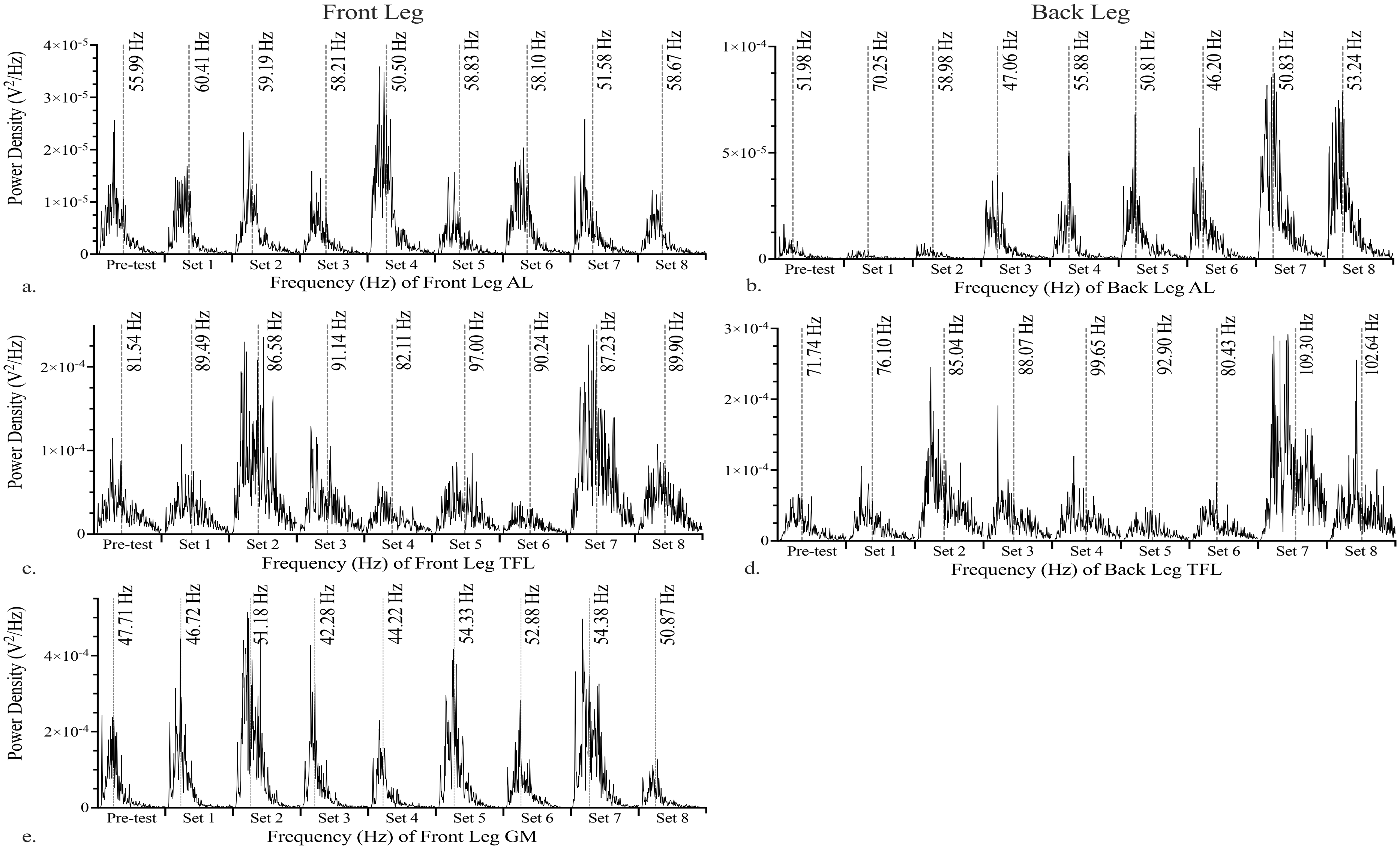


Figure 14. A power spectral density (PSD) of raw EMG signals from the front and back leg adductor longus muscle (a and b), front tensor fascia latae (c), and front and back gluteus medius (d and e) muscles of Subject 3 during abduction. Median frequencies are demonstrated by dashed lines. Each set is presented across a 200 Hz axis. No back leg gluteus medius signal was recorded due to electrode error.

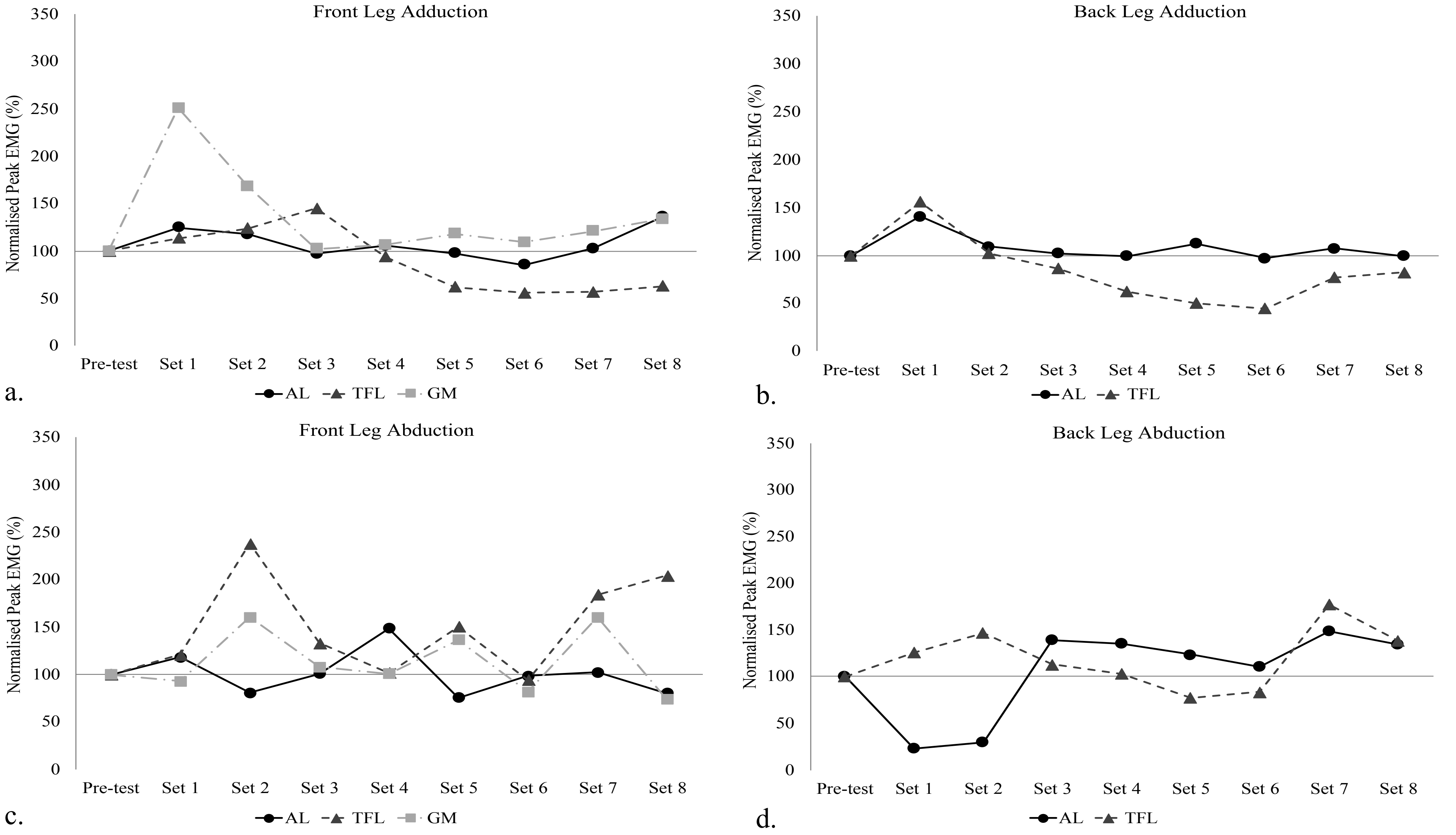
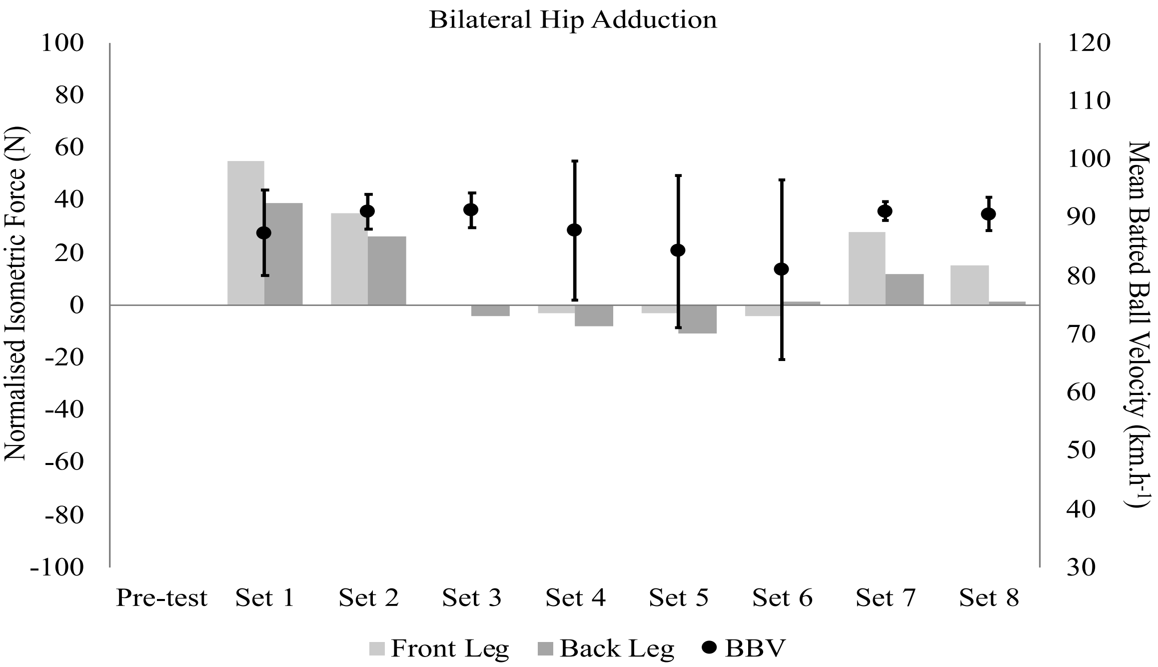
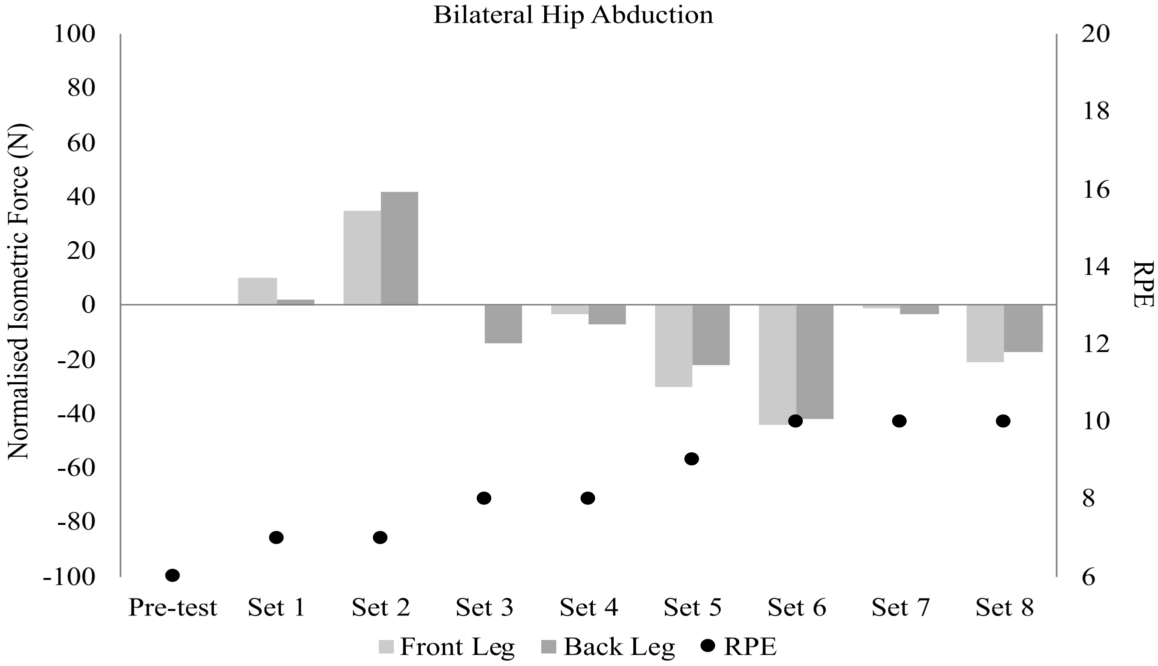


Figure 15. EMG amplitude of Subject 3 during hip adduction (front leg, a; back leg, b) and abduction (front leg, c; back leg, d). Amplitude was normalised to Pre-test amplitude. An increase in amplitude is indicative of increased recruitment of additional motor units. No back leg gluteus medius signal was recorded due to electrode error. AL: Adductor Longus; TFL: Tensor Fascia Latae; GM: Gluteus Medius.



a.



b.

Figure 16. a) Bilateral isometric hip adduction force for Subject 3 normalised to Pre-test values, overlaid with mean batted ball velocities of each set. Error bars denote standard deviations. b) The bilateral isometric hip abduction force of Subject 3 normalised to Pre-test values. Overlaid values are Borg RPE scores reported after each set.

5.3.4 Subject 4

Electrode failure on the back leg TFL muscle of Subject 4 prevented analysis of this muscle. Increases in median frequency during adduction were seen in both AL muscles, the front TFL muscle and the back GM muscle (Figure 24 a-c, e). MDF exhibited an initial increase in frequency followed by shift to lower frequencies in the front GM muscle only (Figure 24d). During abduction, the front leg AL increased in MDF throughout the protocol (Figure 25a). The back leg AL and GM muscles increased, then decreased in overall MDF during abduction (Figures 25b, e), while the front leg TFL and GM muscles decreased in frequency during the protocol (Figures 25c, d). During hip adduction, the normalised EMG amplitude was consistent for all muscles, with some increase. However, the normalised amplitude increase did not occur linearly and may be related to other factors besides fatigue (Figure 26a and b). Similarly, normalised amplitude of the EMG during hip abduction fluctuated above Pre-test values for all muscles, except for the back GM, which decreased (Figure 26c and d).

Subject 4 increased force in both legs during hip adduction by approximately 50 N over Pre-test values to Set 1. Force continued to be higher than Pre-test values throughout all sets, though force began to decline after Set 4 (Figure 27a). Batted ball velocity fluctuated by over 40 $km.h^{-1}$ throughout the protocol, and standard deviations were correspondingly large (±10.7 to 27.1 $km.h^{-1}$) (Figure 27a). During hip abduction, front and back leg force increased from Pre-test to Set 1 but declined throughout the rest of the protocol (Figure 27b). RPE scores increased from 12 to 14 throughout the study (Figure 27b).

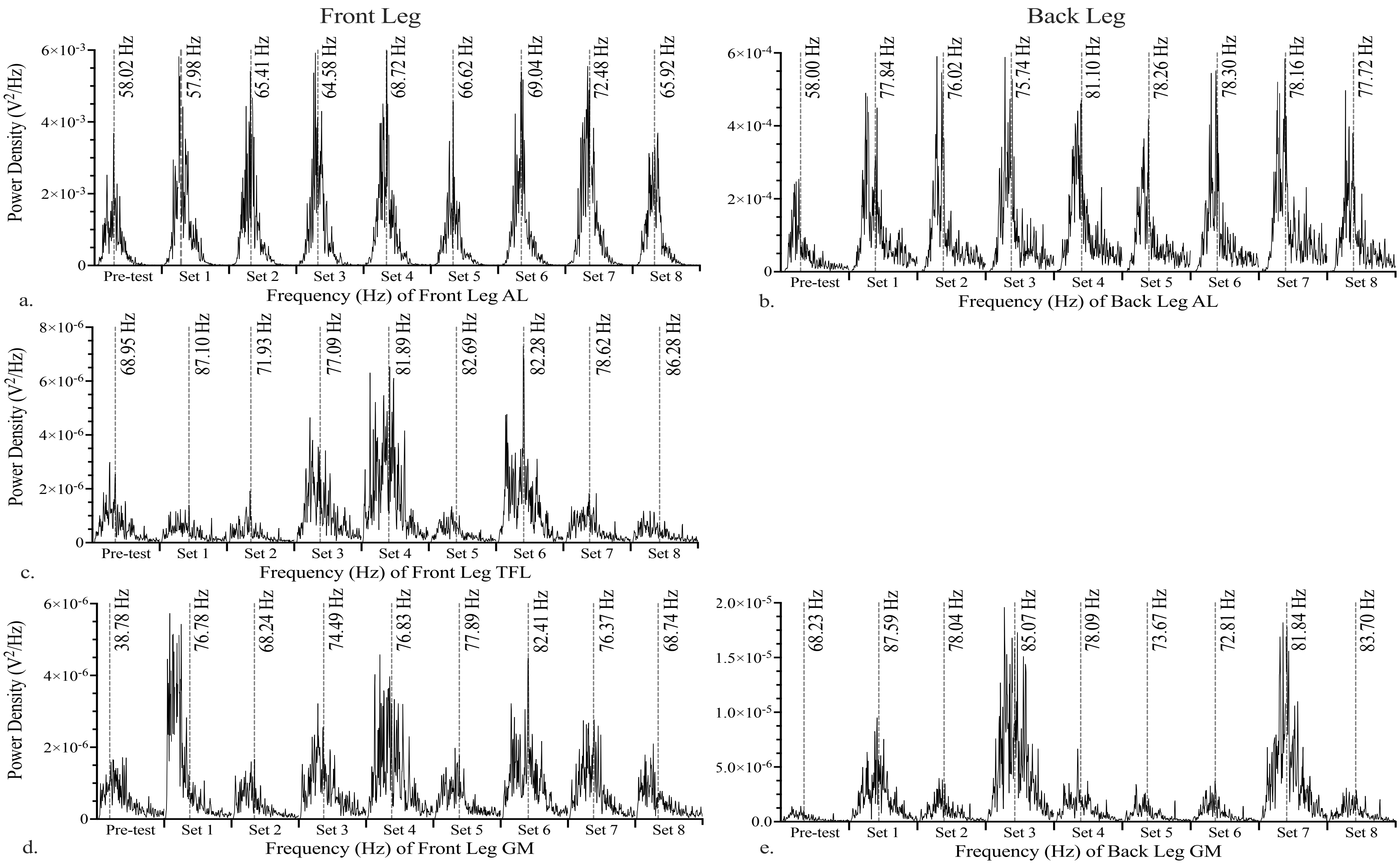


Figure 17. A power spectral density (PSD) of raw EMG signals from the front and back leg adductor longus muscle (a and b), tensor fascia latae (c and d), and gluteus medius (e and f) muscles of Subject 4 during adduction. Median frequencies are demonstrated by dashed lines. Each set is presented across a 200 Hz axis. No back leg tensor fascia latae signal was recorded due to electrode error.

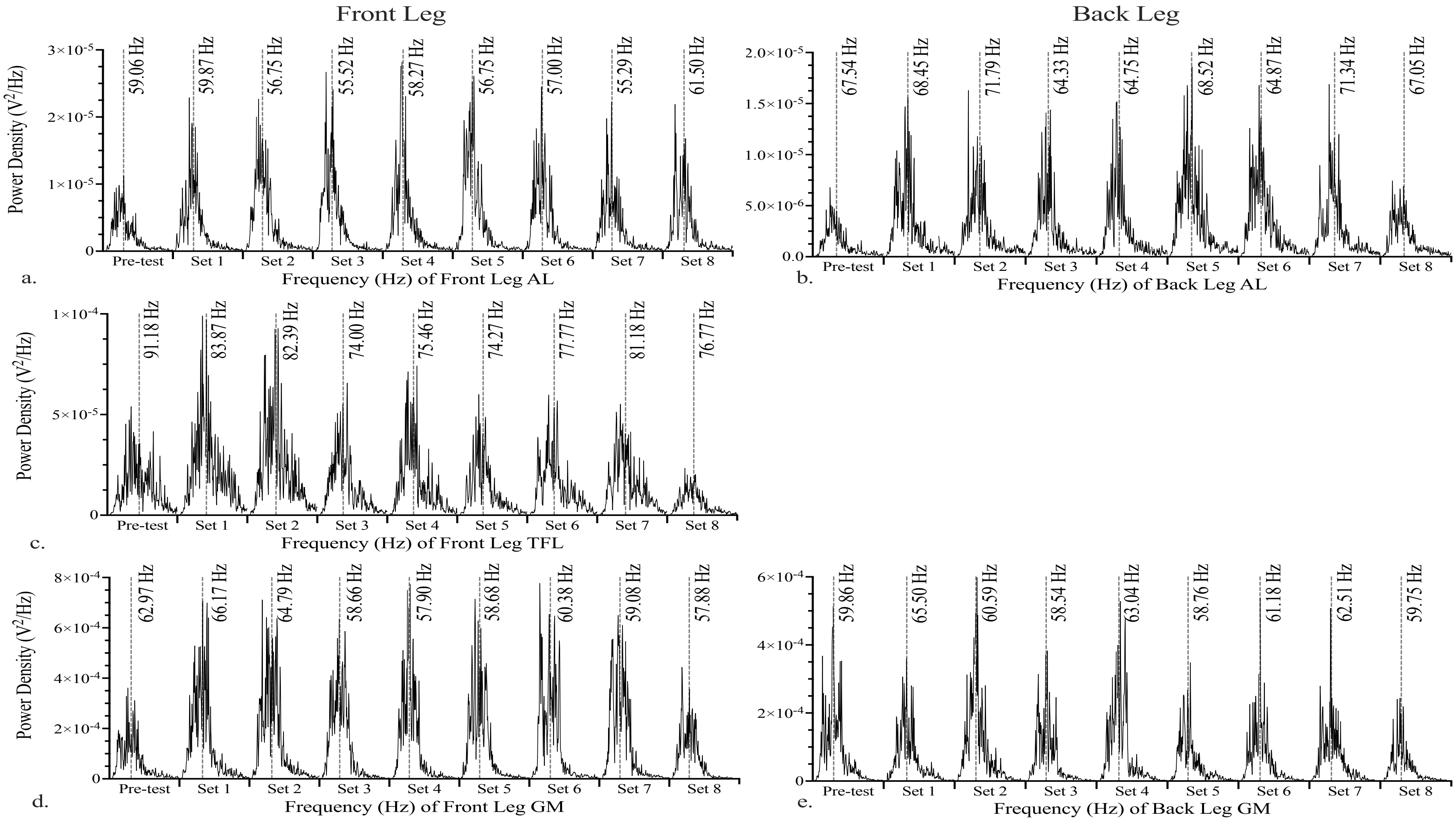


Figure 18. A power spectral density (PSD) of raw EMG signals from the front and back leg adductor longus muscle (a and b), tensor fascia latae (c and d), and gluteus medius (e and f) muscles of Subject 4 during abduction. Median frequencies are demonstrated by dashed lines. Each set is presented across a 200 Hz axis. No back leg tensor fascia latae signal was recorded due to electrode error.

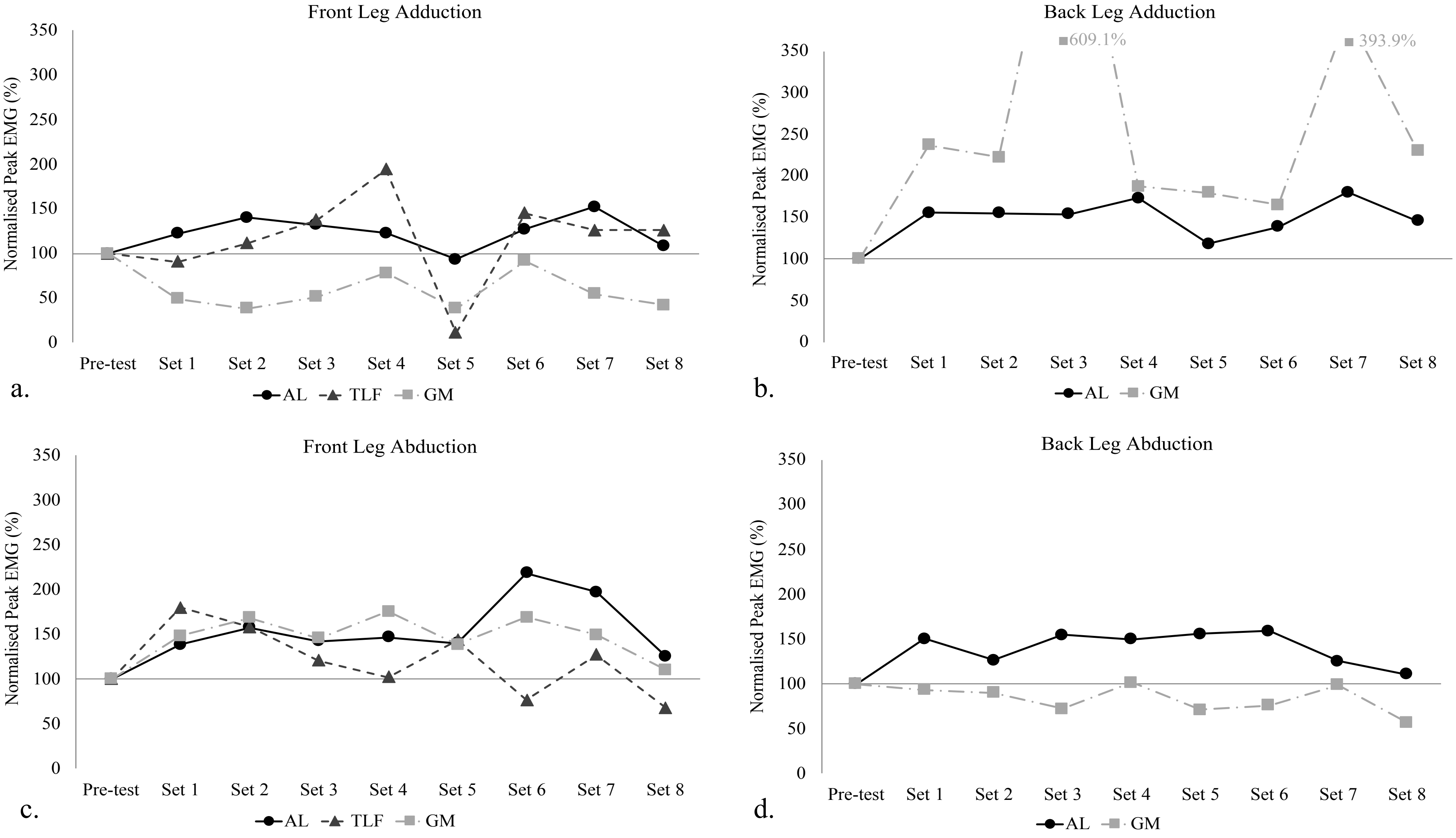


Figure 19. EMG amplitude of Subject 4 during hip adduction (front leg, a; back leg, b) and abduction (front leg, c; back leg, d). Amplitude normalised to Pre-test amplitude. An increase in amplitude is indicative of increased recruitment of additional motor units. No back leg tensor fascia latae signal was recorded due to electrode error.AL: Adductor Longus; TFL: Tensor Fascia Latae; GM: Gluteus Medius.

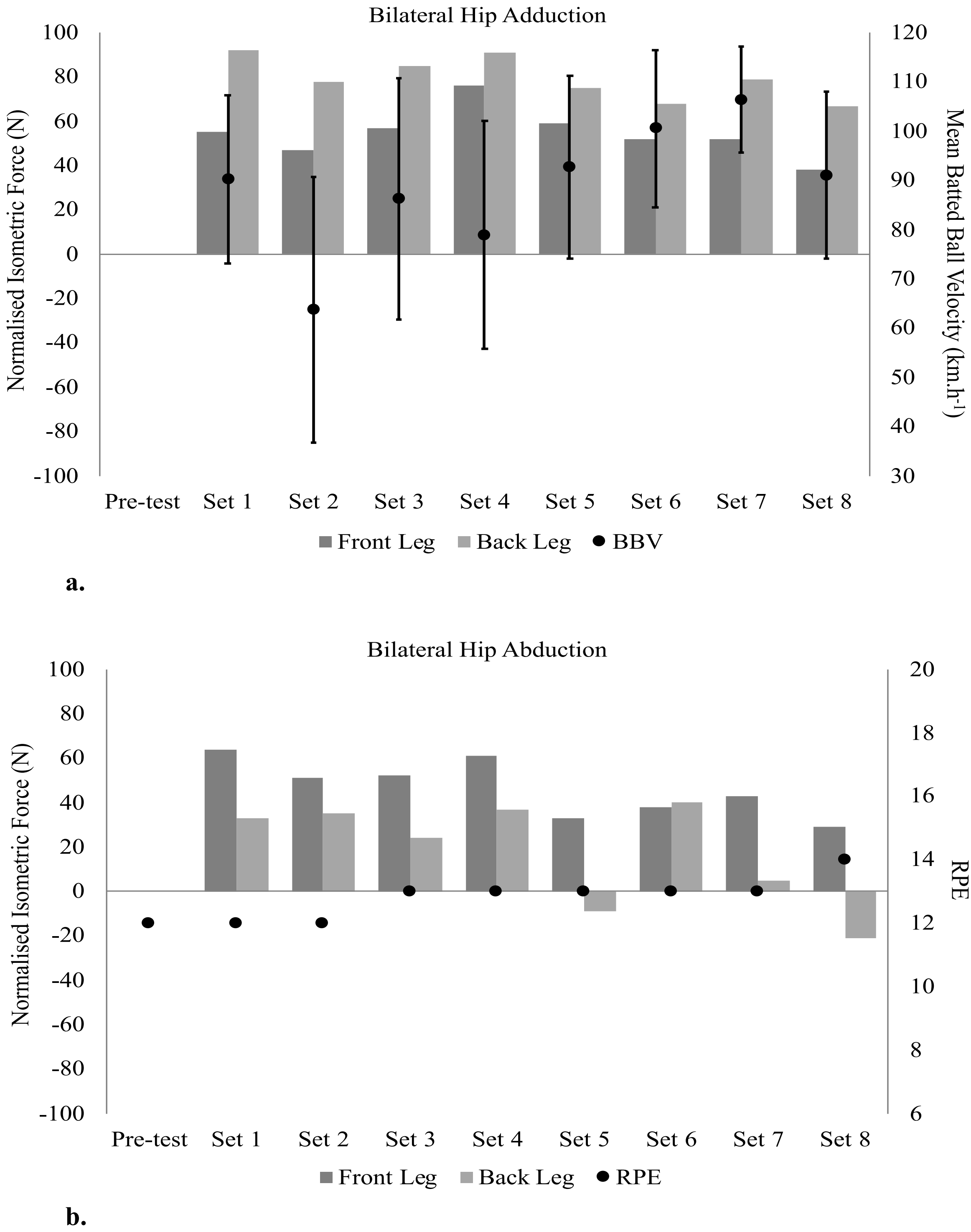


Figure 20. a) Bilateral isometric hip adduction force for Subject 4 normalised to Pre-test values, overlaid with mean batted ball velocities of each set. Error bars denote standard deviations. b) The bilateral isometric hip abduction force of Subject 4 normalised to Pre-test values. Overlaid values are Borg RPE scores reported after each set.

5.4 Discussion

Through a series of case studies, the current study aimed to 1) assess neuromuscular fatigue development measured by EMG and isometric force in hip strength assessments of female softball players intermittently during a repeated batting protocol and 2) evaluate changes in performance variables (e.g. batted ball velocity, RPE) caused by fatigue. Evidence of developing neuromuscular fatigue occurred in all subjects, though amounts varied by individual.

5.4.1 EMG

Cumulative shifts towards lower frequencies occurred in at least two muscles for each subject during the protocol, providing evidence of overall reductions in the number of fast twitch motor units and a greater reliance of slow twitch motor units (Beck et al., 2014; Bigland-Ritchie et al., 1981; Masuda et al., 1999). Subject 1 was the only individual who exhibited this shift in all muscles evaluated. Increases in normalised EMG amplitude across all muscle groups in Subject 1 serves as further confirmation of fatigue development. Subject 1 was also considerably weaker in hip adduction strength than her abduction strength and in comparison to the other subjects. General weakness, and therefore, less fatigue resistance, in the adductor muscle group would explain MDF shifts to lower frequencies in the adductor muscles of Subject 1, while no other subject displayed this response.

Subject 2 displayed cumulative MDF shifts to lower frequencies in both TFL and the back GM muscles. While there was some elevation of normalised amplitude of the EMG in the front and back AL muscles, no clear trend was present in any muscles. This elevation in amplitude may be related to the recruitment of additional motor units and muscle fibres (Hagberg, 1981; Martinez-Valdes et al., 2018; McDonald et al., 2019). As Subject 2 was the only subject who was active in off-season softball training, she was possibly in a more conditioned state, and therefore, may have been more fatigue resistance than the other subjects due to her sport-specific training level at the time.

Subjects 3 and 4 demonstrated cumulative negative shifts in MDF in the front leg TFL and GM muscles, and Subject 3 displayed increases in normalised EMG amplitude of both TFL and the back leg GM muscle. As noted previously, these subjects were trained as slap hitters, though for this study, batted stationary. One could speculate the TFL and GM muscles of these individuals may be more adapted to the run-up phase of slap hitting rather than the infrequent demand to act as stabilisers during a stationary swing. Shifts towards lower frequencies in the TFL and GM muscles of subjects 3 and 4 substantiate this theory. Batters performing a slap hit initiate less torso rotation, which requires significantly less weight transfer and generates less rotational power than in a stationary bat swing (Chang et al., 2011; Washington, 2018). It is unlikely that these two subjects would hit stationary often in training sessions; therefore, fatigue caused by excessive loading during bodyweight transfer may have impacted these subjects more than others. Subject 3 also had not participated in off-season physical training and consequently, more influenced by fatigue. Though Subject 4 displayed some evidence of neuromuscular fatigue (through shifts in MDF), she was active in off-season training for Australian Rules Football, which may have provided her with a conditioning status better able to tolerate the batting protocol.

5.4.2 Isometric Force

During the isometric hip adduction assessment, Subjects 2, 3, and 4 matched or exceeded Pre-test strength values (i.e. peak force) in Sets 7 and 8. Subject 1 surpassed her Pre-test values in Set 3 and remained above through the remainder of the protocol. Similarly, all subjects exceeded their Pre-test hip abduction strength by Set 7 in the back leg. This result was also present in the front legs of Subject 1, 3, and 4. Previous research has demonstrated that athletes apply compensatory mechanisms to counterbalance the loss of force generation due to fatigue (Bonnard et al., 1994; Cowley et al., 2014; Hautier et al., 2000; Pinniger et al., 2000; Sparto et al., 1997). One could speculate the subjects in the current study applied various strategies to maintain strength in the latter sets. Greatest isometric force production each trial also alternated between the front and back legs in all subjects.

5.4.3 Performance Variables

Movement variability to adapt to changing task requirements allows athletes to maintain motor performance across multiple repetitions of a task (Stergiou & Decker, 2011). However, athletes are not immune to the effects of neuromuscular fatigue, which may manifest as pattern changes in muscle activity, increased modulations of isometric force, and alterations in movement dynamics (Cortes et al., 2014). As a result, performance variables such as batted ball velocity can be considered measures of outcome variability. Subjects 1 and 3 were able to maintain batted ball velocity throughout the protocol, though standard deviations of ≥10 km.h^{-1} developed in Sets 2, 6, and 8 for Subject 1 and Sets 4-6 for Subject 3. With eleven and ten years of softball experience, respectively, it is likely that these subjects attempted to make minor modifications to their batting strategy in efforts to maintain batted ball velocity. Though Subject 2 exhibited consistency in her batting strategy (as evidenced with standard deviations <10 km.h^{-1} for all sets), she could not counter the effects of neuromuscular fatigue. Consequently, her batted ball velocity declined by 10 km.h^{-1} throughout the protocol.

In contrast, Subject 4 presented inconsistencies in both batted ball velocity and standard deviation, with a range of 45.8 km.h^{-1} and a standard deviation of ±21.64 km.h^{-1}. In the presence of neuromuscular fatigue, Subject 4 may have demonstrated her increased fatigue level through batted ball velocity rather than other metrics tested in the current study. Further, while Subject 4 had participated in State level teams for several years, her playing history was limited to the past five years. As outcome variability depends on the athlete's skill level (Nakata et al., 2012; Wagner et al., 2012), this subject may continue to develop the ability to make small modifications to her batting stance and swing to maintain performance variables.

It should be noted that bat swing mechanics allow for the flexibility to compensate and adapt to the task constraints to ensure optimal performance (Katsumata, 2007). In addition to adjustments for consistent outcome variables, increased movement variability can protect the athlete from overuse injuries by altering the magnitude, rate, frequency, or application site of a load when in a fatigued state (Edwards et al., 2012). Exercise-induced fatigue is responsible for a decline in force production and, more importantly, impacts the athlete's ability to perform in a smooth and controlled pattern (Cortes et al., 2014). As more acute injuries occur in training than in gameplay for softball players (4.79 practice injuries per 1000 exposures vs. 3.26 game injuries per 1000 exposures) (Patel et al., 2021), regular assessment of performance variables, like batted ball velocity, and the extent of outcome variability through standard deviations may help sport scientists and coaches prevent overuse injuries in softball or baseball players.

5.5 Conclusion

Batting is a fundamental skill in softball and baseball, requiring precise timing and coordination of segmented body movements to propel the ball into play. Pelvic stability is an essential component of a successful transfer of momentum from the lower extremities to the upper extremities (Shaffer et al., 1993; Washington, 2018; Washington et al., 2018). While previous research has described neuromuscular changes in softball or baseball pitchers caused by repeated movements during gameplay, there is limited research on fatigue development as a result of softball batting. While shifts toward lower median frequencies, increases in normalised EMG amplitude, changes in isometric strength and batted ball velocity occurred in all subjects, results varied by individual. As such, it is still inconclusive to what degree repeated batting activities have on the development of neuromuscular fatigue. However, as the present study was short of significant power, it is recommended that a future study be completed with more subjects and investigate the effects of both batting and throwing repetition on neuromuscular fatigue. Meanwhile, we suggest coaches and sport scientists implement regular monitoring of performance variables for softball and baseball players if significant amounts of batting occur with little recovery, such as in a tournament settin

At the request of the author,

Chapter 6 is unavailable in this version of the thesis

CHAPTER SEVEN

General Summary and Conclusion

Summarises research findings and offers suggestions for future avenues of research

7.1 General Summary

The overall purpose of this thesis was to determine the movement demands in softball and examine the development of neuromuscular fatigue in the hip musculature of female softball athletes by assessing physiological demands during training, competitive play, and sport-specific repetitive movements. Additionally, this thesis established the reliability of the ForceFrame Hip Strength Testing system in female diamond-sport athletes unaccustomed to isolated joint isometric assessments in the hip or shoulder regions. This thesis's results may provide a solid foundation in research regarding neuromuscular fatigue in softball players' hip musculature.

Study one (Chapter Three) was the first study to conduct a time-motion analysis of softball games. The results demonstrated that softball is primarily comprised of low intensity activities, like standing or walking, with brief periods of high intensity activity, potentially lasting more than 8 seconds in length. While the greater amount of low intensity movements found in softball may allow for some recovery during gameplay, as is suggested in cricket (Duffield & Drinkwater, 2008), other factors, such as game length, tournament schedules and environmental factors may influence the likelihood of acute muscle fatigue. Additionally, this study presented information that may be used to develop sport-specific training and conditioning programs for individual playing positions, particularly emphasising muscular endurance to counter residual muscular fatigue.

Study two (Chapter Four) determined the ForceFrame was a reliable tool in assessing hip isometric strength in female diamond-sport athletes and offers similar intra-class correlations for hip adduction and abduction in male athletes (Desmyttere et al., 2019; Ryan et al., 2018). This study was also the first to assess isometric shoulder strength and established moderate to high reliability, though CV values were above (or nearly above) the set criterion for reliability (CV: 9.6 – 13.8%). Additional familiarisation periods may lower the CVs in athletes unaccustomed to isometric strength testing. Finally, while this study concluded some agreement exists between the ForceFrame and HHD, these devices should not be used interchangeably due to significant bias and large limits of agreement. Nonetheless, this study demonstrated that the ForceFrame may be a suitable alternative to the HHD in field-based isometric strength testing of female athletes.

Study three (Chapter Five) provided a preliminary investigation into the development of neuromuscular fatigue in softball athletes' hip musculature during batting performances. Though there was variation between subjects, trends in median frequency, EMG amplitude, isometric force and batted ball velocity indicates possible neuromuscular fatigue development. Future research should extend this study to a greater number of subjects and coaches and sport scientists should implement regular monitoring of performance variables for softball players if significant amounts of batting occur with little recovery, such as in a tournament setting.

Study four (Chapter Six) demonstrated significant levels of fatigue following softball training sessions and gameplay, and it indicated that the rate of fatigue development was similar in both settings. Additionally, reductions in isometric strength from pre-training to pre-game ($p < 0.01$) may be indicative of cumulative fatigue development during a multi-day softball tournament, though confirmation of this hypothesis was limited by the small sample of games. While this study looked solely at declines in physical strength, previous research has suggested that mental fatigue may also impact playing performance (Tallent et al., 2017; Veness et al., 2017). Thus, softball players may be subject to added neuromuscular fatigue during multi-day tournaments. The results of this study provide the groundwork for determining an appropriate balance between competition-level training and adequate recovery, though further investigations are needed.

These studies have collectively demonstrated that, though softball is a sport of primarily low intensity activities, the repetitive nature of frequent maximal-effort movements (e.g. bat swings, sprints, high intensity throws) throughout a game or tournament may lead to the manifestation of neuromuscular fatigue and physical performance declines. Changes in the isometric hip or shoulder strength of softball players can serve as a potential indicator of neuromuscular fatigue development, and regular monitoring should occur to minimise the risk of overuse injuries or illness. As successful transfer of momentum from the ground up through the body depends on optimal stabilisation of the hip musculature (Gilmer et al., 2018; Washington et al., 2018), the results from this thesis can lead to the development of sport-specific training and strength and conditioning programs for softball athletes and methods of monitoring neuromuscular fatigue and recovery from training, games, and tournaments.

7.2 Directions for Future Research

Although this thesis has attempted to address gaps within the current literature of softball, there are still opportunities for further research within this topic. Each of the previous studies outlined recommendations for future areas of research; however, additional topics are indicated below:

- As stated before, study 3 should be repeated with a greater number of subjects to fully understand the impact of neuromuscular fatigue following a repetitive batting protocol.

- Future research should also evaluate EMG changes in the hip musculature in response to neuromuscular fatigue developed during repetitive overhand throwing attempts. With study one (Chapter Three) indicating approximately 20 high intensity throws made per position player throughout a game (in both live and dead play settings), the repetitive nature of this movement and the involvement of the whole body to develop power indicate the necessity of this research topic.

- Further investigations of joint specific changes throughout a preseason or lengthy training season would also supplement the successful development of softball-specific strength and conditioning programs. These investigations could utilise isometric strength measurements for specific body regions (hip, shoulder), in addition to common full-body strength tests like the isometric mid-thigh pull or one-repetition maximum tests.

- Additional research should also be conducted to expand the data collected in Chapter 6 to include more games and practice sessions for comparison.

- Finally, with previous research demonstrating declines in performance variables as a result of fatigue development, future studies should evaluate the effect of fatigue on changes in skill acquisition and movement variability during softball-specific movements.

REFERENCES

2018/19 Champions League match and draw calendar. (2018). https://www.uefa.com/uefachampionsleague/matches/format/

Alfuth, M., & Hahm, M. M. (2016). Reliability, comparability, and validity of foot inversion and eversion strength measurements using a hand-held dynamometer. *International Journal of Sports Physical Therapy, 11*(1), 72-84. http://ezproxy.ecu.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=26900502&site=ehost-live&scope=site

Asmussen, E. (1979). Muscle fatigue. *Medicine and Science in Sports, 11*(4), 313-321.

Axe, M. J., Windley, T. C., & Snyder-Mackler, L. (2002). Data-based interval throwing programs for collegiate softball players. *Journal of Athletic Training, 32*(2), 194-203.

Babault, N., Desbrosses, K., Fabre, M. S., Michaut, A., & Pousson, M. (2006). Neuromuscular fatigue development during maximal concentric and isometric knee extensions. *Journal of Applied Physiology, 100*(3), 780-785. https://doi.org/10.1152/japplphysiol.00737.2005

Barrentine, S. W., Fleisig, G. S., Whiteside, J. A., Escamilla, R. F., & Andrews, J. R. (1998). Biomechanics of windmill softball pitching with implications about injury mechanisms at the shoulder and elbow. *Journal of Orthopaedic and Sports Physical Therapy, 28*(405-414).

Barrett, D. D., & Burton, A. W. (2002). Throwing patterns used by collegiate baseball players in actual games. *Research Quarterly for Exercise and Sport, 73*(1), 19-27. https://doi.org/10.1080/02701367.2002.10608988

Barry, B. K., & Enoka, R. M. (2007). The neurobiology of muscle fatigue: 15 years later. *Integrative and Comparative Biology, 47*(4), 465-473. https://doi.org/10.1093/icb/icm047

Baumgartner, T. A., & Chung, H. (2001). Confidence limits for intraclass reliability coefficients. *Measurement in Physical Education & Exercise Science, 5*(3), 179-188. http://ezproxy.ecu.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=5209576&site=ehost-live&scope=site

Beaven, R. P., Highton, J. M., Thorpe, M.-C., Knott, E. V., & Twist, C. (2014). Movement and physiological demands of international and regional men's touch rugby matches. *Journal of Strength and Conditioning Research, 28*(11), 3274-3279. http://ezproxy.ecu.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=s3h&AN=99415874&site=ehost-live&scope=site

Beck, T. W., Stock, M. S., & Defreitas, J. M. (2014). Shifts in EMG spectral power during fatiguing dynamic contractions. *Muscle and Nerve, 50*(1), 95-102. https://doi.org/10.1002/mus.24098

Bigland-Ritchie, B., Donovan, E. F., & Roussos, C. S. (1981). Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *Journal of Applied Physiology, 51*(5), 1300-1305. https://doi.org/10.1152/jappl.1981.51.5.1300

Bigland-Ritchie, B., Johansson, R., Lippold, C. J., & Woods, J. J. (1983). Contractile speed and EMG changes during fatigue of sustained MVC. *Journal of Neurophysiology, 50*(1), 313-324.

Bigland-Ritchie, B., Jones, D. A., Hosking, G. P., & Edwards, R. H. T. (1978). Central and peripheral fatigue in sustained maximal voluntary contractions of human quadriceps muscle. *Clinical Science and Molecular Medicine, 54*, 609-614.

Bigland-Ritchie, B., Thomas, C. K., Rice, C. L., Howarth, J. V., & Woods, J. J. (1992). Muscle temperature, contractile speed, and motoneuron firing rates during human voluntary contractions. *Journal of Applied Physiology, 73*, 2457-2461.

Bigland-Ritchie, B., Zijdewind, I., & Thomas, C. K. (2000). Muscle fatigue induced by stimulation with and without doublets. *Muscle and Nerve, 23*(9), 1348-1355. https://doi.org/10.1002/1097-4598(200009)23:9<1348::AID-MUS5>3.0.CO;2-0

Bird, S. P. (2019). *Role of sports science in fatigue monitoring and recovery management of Olympic athletes.* Conference on Interdisciplinary Approach in Sports (CoIS 2019), Yogyakarta, Indonesia.

Bishop, P. A., Jones, E., & Woods, A. K. (2008). Recovery from training: A brief review. *Journal of Strength and Conditioning Research, 22*(3), 1015-1024.

Bloomfield, J., Polman, R., & O'Donoghue, P. (2007). Physical demands of different positions in FA Premier League soccer. *Journal of Sports Science & Medicine, 6*, 63-70.

Bonnard, M., Sirin, A. V., Oddsson, L., & Thorstensson, A. (1994). Different strategies to compensate for the effects of fatigue revealed by neuromuscular adaption processes in humans. *Neuroscience Letters, 116*, 101-105.

Borg, G. A. V. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sport and Exercise, 14*(5), 377-381.

Bounds, E. M. (2010). *Effects of a functional fatigue protocol on softball hitting.* University of Central Oklahoma].

Boyas, S., & Guevel, A. (2011). Neuromuscular fatigue in healthy muscle: underlying factors and adaptation mechanisms. *Annals of Physical and Rehabilitation Medicine, 54*(2), 88-108. https://doi.org/10.1016/j.rehab.2011.01.001

Buchheit, M., McHugh, D., & Smith, S. (2021). Kitman Labs Performance Intelligence Research Initiative: A survey to bring research on the field. *Sports Performance & Science Reports, 135*(1), 1-6.

Buchheit, M., Morgan, W., Wallace, J., Bode, M., & Poulos, N. (2017). Monitoring post-match lower-limb recovery in elite Australian Rules Football using a groin squeeze strength test. *Sports Performance & Science Reports, 7*(1), 1-3.

Cahill, S., & Jones, M. T. (2010). Measurement of body composition and athletic performance during NCAA-Division I women's volleyball and softball seasons. *Journal of Strength and Conditioning Research, 24*, 1.

Campbell, B. M., Stodden, D. F., & Nixon, M. K. (2010). Lower extremity muscle activation during baseball pitching. *Journal of Strength and Conditioning Research, 24*(4), 964-971.

Cardwell, K. (2021). *Assessment of performance, movement demands, and neuromuscular fatigue in female softball players* [Doctoral Dissertation, Edith Cowan University].

Carroll, T. J., Taylor, J. L., & Gandevia, S. C. (2017). Recovery of central and peripheral neuromuscular fatigue after exercise. *J Appl Physiol (1985), 122*(5), 1068-1076. https://doi.org/10.1152/japplphysiol.00775.2016

Chang, Y.-W., Hsieh, H.-M., Yang, S.-M., Chen, F.-Y., Lin, H.-W., & Wu, H.-W. (2011). Comparison of torso twist between slap hit and ordinary hit in softball batting. *Portuguese Journal of Sport Science, 11*, 61-63.

Chang, Y.-W., Yang, S.-M., Chen, F.-Y., & Wu, H.-W. (2010). Electromyographic factors correlated with softball batting performance. *ISBS-Conference Proceedings Archive, 1*(1).

Christ, C. B., Slaughter, M. H., Stillman, R. J., Cameron, J., & Boileau, R. A. (1994). Reliability of select parameters of isometric muscle function associated with testing 3 days × 3 trials in women. *The Journal of Strength & Conditioning Research, 8*(2). https://journals.lww.com/nsca-jscr/Fulltext/1994/05000/Reliability_of_Select_Parameters_of_Isometric.1.aspx

Christie, C. J. (2012). The physical demands of batting and fast bowling in cricket. In *An International Perspective on Topics in Sports Medicine and Sports Injury*. InTech.

Christie, C. J., Sheppard, B., Goble, D., Pote, L., & Noakes, T. D. (2019). Strength and sprint time changes in response to repeated shuttles between the wickets during batting in cricket. *Journal of Strength and Conditioning Research, 33*(11), 3056-3064.

Cifrek, M., Medved, V., Tonkovic, S., & Ostojic, S. (2009). Surface EMG based muscle fatigue evaluation in biomechanics. *Clinical Biomechanics (Bristol, Avon), 24*(4), 327-340. https://doi.org/10.1016/j.clinbiomech.2009.01.010

Clarke, A. C., Anson, J. M., & Pyne, D. B. (2015). Neuromuscular fatigue and muscle damage after a women's rugby sevens tournament. *International Journal of Sports Physiology and Performance, 10*(6), 808-814. https://doi.org/10.1123/ijspp.2014-0590

Cooke, K., Outram, T., Brandon, R., Waldron, M., Vickery, W., Keenan, J., & Tallent, J. (2019). The difference in neuromuscular fatigue and workload during competition and training in elite cricketers. *International Journal of Sports Physiology and Performance, 14*(4), 439-444. https://doi.org/10.1123/ijspp.2018-0415

Cools, A. M., Vanderstukken, F., Vereecken, F., Duprez, M., Heyman, K., Goethals, N., & Johansson, F. (2016). Eccentric and isometric shoulder rotator cuff strength testing using a hand-held dynamometer: Reference values for overhead athletes. *Knee Surgery, Sports Traumatology, Arthroscopy, 24*, 3838-3847. https://doi.org/10.1007/s00167-015-3755-9

Corben, J. S., Cerrone, S. A., Soviero, J. E., Kwiecien, S. Y., Nicholas, S. J., & McHugh, M. P. (2015). Performance demands in softball pitching: A comprehensive muscle fatigue study. *American Journal of Sports Medicine, 43*(8), 2035-2041. https://doi.org/10.1177/0363546515588179

Cormack, S. J., Newton, R. U., & McGuigan, M. R. (2008). Neuromuscular and endocrine responses of elite players to an Australian Rules Football match. *International Journal of Sports Physiology and Performance, 3*, 359-374.

Cortes, N., Onate, J., & Morrison, S. (2014). Differential effects of fatigue on movement variability. *Gait and Posture, 39*(3), 888-893. https://doi.org/10.1016/j.gaitpost.2013.11.020

Cortes, N., Quammen, D., Lucci, S., Greska, E., & Onate, J. (2012). A functional agility short-term fatigue protocol changes lower extremity mechanics. *Journal of Sports Sciences, 30*(8), 797-805. https://doi.org/10.1080/02640414.2012.671528

Coutts, A. J., & Duffield, R. (2010). Validity and reliability of GPS devices for measuring movement demands of team sports. *Journal of Science and Medicine in Sport, 13*(1), 133-135. https://doi.org/10.1016/j.jsams.2008.09.015

Coutts, A. J., Quinn, J., Hocking, J., Castagna, C., & Rampinini, E. (2010). Match running performance in elite Australian Rules Football. *Journal of Science and Medicine in Sport, 13*(5), 543-548. https://doi.org/10.1016/j.jsams.2009.09.004

Cowley, J. C., Dingwell, J. B., & Gates, D. H. (2014). Effects of local and widespread muscle fatigue on movement timing. *Experimental Brain Research, 232*(12), 3939-3948. https://doi.org/10.1007/s00221-014-4020-z

Cram, J. R. (2011). *Introduction to Surface Electromyography* (E. Criswell, Ed. 2 ed.). Jones and Bartlett Publishers.

Crow, J. F., Pearce, A. J., Veale, J. P., VanderWesthuizen, D., Coburn, P. T., & Pizzari, T. (2010). Hip adductor muscle strength is reduced preceding and during the onset of groin pain in elite junior Australian football players. *Journal of Science and Medicine in Sport, 13*(2), 202-204. https://doi.org/10.1016/j.jsams.2009.03.007

D’Auria, S., & Gabbett, T. (2008). A time-motion analysis of international women's water polo match play. *International Journal of Sports Physiology and Performance, 3*, 305-319.

Dawson, B., Hopkinson, R., Appleby, B., Stewart, G., & Roberts, C. (2004). Comparison of training activities and game demands in the Australian football league. *Journal of Science and Medicine in Sport, 7*(3), 292-301.

De Luca, C. J. (1979). Physiology and mathmatics of myoelectric signals. *IEEE Transactions on Biomedical Engineering, 26*(6), 313-325.

De Luca, C. J., Sabbahi, M. A., Stulen, F. B., & Bilotto, G. (1983). Some properties of the median frequency of the myoelectric signal during localized muscular fatigue. *Biochemistry of Exercise (International Series on Sport Sciences), 13*, 175-186.

Decorte, N., Lafaix, P. A., Millet, G. Y., Wuyam, B., & Verges, S. (2012). Central and peripheral fatigue kinetics during exhaustive constant-load cycling. *Scandinavian Journal of Medicine and Science in Sports, 22*(3), 381-391. https://doi.org/10.1111/j.1600-0838.2010.01167.x

Delahunt, E., Kennelly, C., McEntee, B. L., Coughlan, G. F., & Green, B. S. (2011). The thigh adductor squeeze test: 45 degrees of hip flexion as the optimal test position for eliciting adductor muscle activity and maximum pressure values. *Manual Therapy, 16*(5), 476-480. https://doi.org/10.1016/j.math.2011.02.014

DeRenne, C., Buxton, B. P., Hetzler, R. K., & Ho, K. W. (1995). Effects of weighted bat implement training on bat swing velocity. *Journal of Strength and Conditioning Research, 9*(4), 247-250.

Deschenes, M. (1989). Short review: Rate coding and motor unit recruitment patterns. *Journal of Applied Sports Science Research, 3*(2), 33-39.

Desmyttere, G., Gaudet, S., & Begon, M. (2019). Test-retest reliability of a hip strength assessment system in varsity soccer players. *Physical Therapy in Sport, 37*, 138-143. https://doi.org/10.1016/j.ptsp.2019.03.013

Deutsch, M. U., Kearney, G. A., & Rehrer, N. J. (2007). Time-motion analysis of professional rugby union players during match-play. *Journal of Sports Sciences, 25*(4), 461-472. https://doi.org/10.1080/02640410600631298

Dilodeau, M., Cincera, M., Gervais, S., Arsenault, A. B., Gravel, D., Lepage, Y., & McKinley, P. (1995). Changes in the electromyographic spectrum power distribution caused by a progressive increase in the force level. *European Journal of Applied Physiology, 71*, 113-123.

Dimitrova, N. A., & Dimitrov, G. V. (2003). Interpretation of EMG changes with fatigue: facts, pitfalls, and fallacies. *Journal of Electromyography and Kinesiology, 13*(1), 13-36. https://doi.org/10.1016/s1050-6411(02)00083-4

Doeven, S. H., Brink, M. S., Kosse, S. J., & Lemmink, K. (2018). Postmatch recovery of physical performance and biochemical markers in team ball sports: A systematic review. *BMJ Open Sport Exerc Med, 4*(1), e000264. https://doi.org/10.1136/bmjsem-2017-000264

Duffield, R., & Drinkwater, E. J. (2008). Time-motion analysis of test and one-day international cricket centuries. *Journal of Sports Sciences, 26*(5), 457-464. https://doi.org/10.1080/02640410701644026

Duthie, G., Pyne, D., & Hooper, S. (2003). The reliability of video based time motion analysis. *Journal of Human Movement Studies, 44*, 259-272.

Duthie, G., Pyne, D., & Hooper, S. (2005). Time motion analysis of 2001 and 2002 super 12 rugby. *Journal of Sports Sciences, 23*(5), 523-530. https://doi.org/10.1080/02640410410001730188

Edwards, S., Steele, J. R., Cook, J., Purdam, C., & McGhee, D. (2012). Effects of fatigue on movement variability during stretch-shortening cycle. 30th Annual Conference of Biomechanics in Sports, Melbourne, AUS.

Enoka, R. M. (2008). *Neuromechanics of Human Movement* (4th ed.). Human Kinetics.

Enoka, R. M., Baudry, S., Rudroff, T., Farina, D., Klass, M., & Duchateau, J. (2011). Unraveling the neurophysiology of muscle fatigue. *Journal of Electromyography and Kinesiology, 21*(2), 208-219. https://doi.org/10.1016/j.jelekin.2010.10.006

Enoka, R. M., & Stuart, D. G. (1992). Neurobiology of muscle fatigue. *Journal of Applied Physiology, 72*(5), 1631-1648.

Escamilla, R. F., Barrentine, S. W., Fleisig, G. S., Zheng, N., Takada, Y., Kingsley, D., & Andrews, J. R. (2007). Pitching biomechanics as a pitcher approaches muscular fatigue during a simulated baseball game. *American Journal of Sports Medicine, 35*(1), 23-33. https://doi.org/10.1177/0363546506293025

Farina, D., Merletti, R., & Enoka, R. M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology, 96*, 1486-1495.

Fauth, M. L., Petushek, E. J., Feldmann, C. R., Hsu, B. E., Garceau, L. R., Lutsch, B. N., & Ebben, W. P. (2010). Reliability of surface electromyography during maximal voluntary isometric contractions, jump landings, and cutting. *Journal of Strength and Conditioning Research, 24*(4), 1131-1137.

Flyger, N., Button, C., & Rishiraj, N. (2006). The science of softball: Implications for performance and injury prevention. *Sports Medicine, 36*(9), 797-816.

Forshaw, B., Wu, T., Postlmayr, C., & Laquale, K. (2013). *The effect of fatiguability in lower extremity coordination patterns in softball pitching* American Society of Biomechanics, Omaha, NE.

Fortenbaugh, D. (2011). *The biomechanics of the baseball swing.* University of Miami].

Freeston, J., Adams, R., Ferdinands, R. E. D., & Rooney, K. (2014). Indicators of throwing arm fatigue in elite adolescent male baseball players: A randomized crossover trial. *Journal of Strength and Conditioning Research, 28*(8), 2115-2120.

Froyd, C., Beltrami, F. G., Millet, G. Y., & Noakes, T. D. (2016). Central regulation and neuromuscular fatigue during exercise of different durations. *Medicine and Science in Sports and Exercise, 48*(6), 1024-1032. https://doi.org/10.1249/MSS.0000000000000867

Fulcher, M. L., Hanna, C. M., & Raina Elley, C. (2010). Reliability of handheld dynamometry in assessment of hip strength in adult male football players. *Journal of Science and Medicine in Sport, 13*(1), 80-84. https://doi.org/10.1016/j.jsams.2008.11.007

Gandevia, S. C. (1998). Neural control in human muscle fatigue: Changes in muscle afferents, moto neurones and moto cortical drive. *Acta Physiologica Scandinavica, 162*, 275-283.

Gandevia, S. C., Allen, G. M., Butler, J. E., & Taylor, J. L. (1996). Supraspinal factors in human muscle fatigue: Evidence for suboptimal output from the motor cortex. *Journal of Physiology, 490*(2), 529-536.

General Physical Activities Defined by Level of Intensity. (2011). https://www.cdc.gov/nccdphp/dnpa/physical/pdf/pa_intensity_table_2_1.pdf

Gescheit, D. T., Cormack, S. J., Reid, M., & Duffield, R. (2015). Consecutive days of prolonged tennis match play: Performance, physical, and perceptual responses in trained players. *International Journal of Sports Physiology and Performance, 10*(7), 913-920. https://doi.org/10.1123/ijspp.2014-0329

Gescheit, D. T., Duffield, R., Skein, M., Brydon, N., Cormack, S. J., & Reid, M. (2017). Effects of consecutive days of match play on technical performance in tennis. *Journal* *of Sports Sciences, 35*(20), 1988-1994. https://doi.org/10.1080/02640414.2016.1244352

Gilmer, G., Washington, J., & Oliver, G. (2018). Assessment of lumbopelvic–hip complex instability and segmental sequencing amongst softball athletes. *International Biomechanics*, 1-10. https://doi.org/10.1080/23335432.2018.1481456

Gonzalez-Izal, M., Malanda, A., Gorostiaga, E., & Izquierdo, M. (2012). Electromyographic models to assess muscle fatigue. *Journal of Electromyography and Kinesiology, 22*(4), 501-512. https://doi.org/10.1016/j.jelekin.2012.02.019

Goodall, S., Thomas, K., Harper, L. D., Hunter, R., Parker, P., Stevenson, E., West, D., Russell, M., & Howatson, G. (2017). The assessment of neuromuscular fatigue during 120 min of simulated soccer exercise. *European Journal of Applied Physiology, 117*(4), 687-697. https://doi.org/10.1007/s00421-017-3561-9

Guido Jr., J. A., Werner, S. L., & Meister, K. (2009). Lower-extremity ground reaction forces in youth windmill softball players. *Journal of Strength and Conditioning Research, 23*(6), 1873-1876.

Hagberg, M. (1981). Muscular endurance and surface electromyogram in isometric and dynamic exercise. *Journal of Applied Physiology, 51*(1), 1-7.

Hägg, G. M. (1992). Interpretation of EMG spectral alterations and alteration indexes at sustained contractions. *Journal of Applied Physiology, 73*(4), 1211-1217.

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports Medicine, 44*(S2), 139-147. https://doi.org/10.1007/s40279-014-0253-z

Hautier, C. A., Arsac, L. M., Deghdegh, K., Souquet, J., Belli, A., & Lacour, J.-R. (2000). Influence of fatigue on EMG/force ratio and cocontraction in cycling. *Medicine and Science in Sport and Exercise, 32*(4), 839-843.

Hoffman, J. R., Vazquez, J., Pichardo, N., & Tenenbaum, G. (2009). Anthropometric and performance comparisons in professional baseball players. *Journal of Strength and Conditioning Research, 23*(8), 2173-2178.

Holt, K. L., Raper, D. P., Boettcher, C. E., Waddington, G. S., & Drew, M. K. (2016). Hand-held dynamometry strength measures for internal and external rotation demonstrate superior reliability, lower minimal detectable change and higher correlation to isokinetic dynamometry than externally-fixed dynamometry of the shoulder. *Physical Therapy In Sport, 21*, 75-81. https://doi.org/10.1016/j.ptsp.2016.07.001

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1-15.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise, 41*(1), 3-12.

Houghton, L., & Dawson, B. (2012). Short report: Recovery of jump performance after a simulated cricket batting innings. *Journal of Sports Sciences, 30*(10), 1069-1072. https://doi.org/10.1080/02640414.2012.687113

HSBC Sevens Series Rounds. (2018). https://www.worldrugby.org/sevens-series/calendar

Hunter, S. K., Duchateau, J., & Enoka, R. M. (2004). Muscle fatigue and the mechanisms of task failure. *Exercise and Sport Sciences Reviews, 32*(2), 44-49.

Ireland, D., Dawson, B., Peeling, P., Lester, L., Heasman, J., & Rogalski, B. (2019). Do we train how we play? Investigating skill patterns in Australian football. *Science and Medicine in Football, 3*(4), 265-274. https://doi.org/10.1080/24733938.2019.1595111

Jackson, S. M., Cheng, M. S., Smith, A. R., Jr., & Kolber, M. J. (2017). Intrarater reliability of hand held dynamometry in measuring lower extremity isometric strength using a portable stabilization device. *Musculoskelet Sci Pract, 27*, 137-141. https://doi.org/10.1016/j.math.2016.07.010

Jeffreys, I. (2016). Warm-up and flexibility training. In G. G. Haff & N. T. Triplett (Eds.), *Essentials of Strength Training and Conditioning* (4th ed.). Human Kinetics.

Jennings, D., Cormack, S. J., Coutts, A. J., Boyd, L., & Aughey, R. J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International Journal of Sports Physiology and Performance, 5*, 328-341.

Kadlec, D., Griffths, K. M., Young, J. D., & Downes, P. (2019). Adductor strength relationship in different hip positions in male rugby union athletes. *Sports Performance & Science Reports, 72*(1), 1-4.

Kadlec, D., Jordan, M. J., Snyder, L., Alderson, J., & Nimphius, S. (2021). Test re-test reliability of single and multijoint strength properties in female Australian footballers. *Sports Med Open, 7*(1), 5. https://doi.org/10.1186/s40798-020-00292-5

Katoh, M. (2015). Test-retest reliability of isometric shoulder muscle strength measurement with a handheld dynamometer and belt. *Journal of Physical Therapy Science, 27*, 1719-1722.

Katsumata, H. (2007). A functional modulation for timing a movement: A coordinative structure in baseball hitting. *Hum Mov Sci, 26*(1), 27-47. https://doi.org/10.1016/j.humov.2006.09.005

Kay, D., St Clair Gibson, A., Mitchell, M. J., Lambert, M. I., & Noakes, T. D. (2000). Different neuromuscular recruitment patterns during eccentric, concentric and isometric contractions. *Journal of Electromyography and Kinesiology, 10*, 425-431.

Kellett, A. D. (2017). A brief review of the strength and power influences on various overhead throwing sports with specific reference to improving throwing velocity. *Journal of Australian Strength and Conditioning, 25*(2), 45-56.

Kellis, E., & Katis, A. (2008). Reliability of EMG power-spectrum and amplitude of the semitendinosus and biceps femoris muscles during ramp isometric contractions.

Journal of Electromyography and Kinesiology, 18(3), 351-358. https://doi.org/https://doi.org/10.1016/j.jelekin.2006.12.001

Kibler, W. B. (1998). The role of the scapula in athletic shoulder function. *The American Journal of Sports Medicine, 26*(2), 325-337.

Kibler, W. B., Press, J., & Sciascia, A. (2006). The role of core stability in athletic function. *Sports Medicine, 36*(3), 189-198.

Konrad, P. (2005). *The ABC of EMG: A practical introduction to kinesiological electromyography*.

Krause, D. A., Schlagel, S. J., Stember, B. M., Zoetewey, J. E., & Hollman, J. H. (2007). Influence of lever arm and stabilization on measures of hip abduction and adduction torque obtained by hand-held dynamometry. *Archives of Physical Medicine and Rehabilitation, 88*(1), 37-42. https://doi.org/10.1016/j.apmr.2006.09.011

Laudner, K. G., Moore, S. D., Sipes, R. C., & Meister, K. (2010). Functional hip characteristics of baseball pitchers and position players. *American Journal of Sports Medicine, 38*(2), 383-387. https://doi.org/10.1177/0363546509347365

Lovell, G. A., Blanch, P. D., & Barnes, C. J. (2012). EMG of the hip adductor muscles in six clinical examination tests. *Physical Therapy in Sport 13*(3), 134-140. https://doi.org/10.1016/j.ptsp.2011.08.004

Lowe, H. E., Szymanski, D. J., Bankston, B., Braswell, M. T., Britt, A. T., Gilliam, S. T., Herring, A. L., Holloway, B. T., Lowe, D. W., Potts, J. D., Szymanski, J. M., & Till, M. E. (2010). Relationship between body composition and bat swing velocity of college softball players. *Journal of Strength and Conditioning Research, 24*, 1.

Maffet, M. W., Jobe, F. W., Pink, M. M., Brault, J., & Mathiyakom, W. (1997). Shoulder muscle firing patterns during the windmill softball pitch. *The American Journal of Sports Medicine, 25*(3), 369-374.

Marcora, S. M., Staiano, W., & Manning, V. (2009). Mental fatigue impairs physical performance in humans. *J Appl Physiol (1985), 106*(3), 857-864. https://doi.org/10.1152/japplphysiol.91324.2008

Martinez-Valdes, E., Negro, F., Falla, D., De Nunzio, A. M., & Farina, D. (2018). Surface electromyographic amplitude does not identify differences in neural drive to synergistic muscles. *J Appl Physiol (1985), 124*(4), 1071-1079. https://doi.org/10.1152/japplphysiol.01115.2017

Masuda, K., Masuda, T., Sadoyama, T., Mitsuharu, I., & Katsuta, S. (1999). Changes in surface EMG parameters during static and dynamic fatiguing contractions. *Journal of Electromyography and Kinesiology, 9*(1), 39-46. https://doi.org/10.1016/s1050-6411(98)00021-2

Maton, B. (1981). Human motor unit activity during the onset of muscle fatigue in submaximal isometric contraction. *European Journal of Applied Physiology, 46*, 271-281.

McArdle, W. D., Katch, V. L., & Katch, F. I. (2015). *Exercise Physiology: Energy, nutrition and human performance*. Williams & Wilkins.

McDonald, A. C., Mulla, D. M., & Keir, P. J. (2019). Using EMG amplitude and frequency to calculate a multimuscle fatigue score and evaluate global shoulder fatigue. *Human Factors, 61*(4), 526-536. https://doi.org/10.1177/0018720818794604

McGuigan, H., Hassmén, P., Rosic, N., & Stevens, C. J. (2020). Training monitoring methods used in the field by coaches and practitioners: A systematic review. *International Journal of Sports Science & Coaching, 15*(3), 439-451. https://doi.org/10.1177/1747954120913172

McInnes, S. E., Carlson, J. S., Jones, C. J., & McKenna, M. J. (1995). The physiological load imposed on basketball players during competition. *Journal of Sports Sciences, 13*(5), 387-397. https://doi.org/10.1080/02640419508732254

McLellan, C. P., & Lovell, D. I. (2012). Neuromuscular responses to impact and collision during elite rugby league match play. *Journal of Strength and Conditioning Research, 26*(5), 1431-1440.

McNamara, D. J., Gabbett, T. J., Naughton, G., Farhart, P., & Chapman, P. (2013). Training and competition workloads and fatigue responses of elite junior cricket players. *International Journal of Sports Physiology and Performance, 8*, 517-526.

McNeil, C. J., Giesebrecht, S., Gandevia, S. C., & Taylor, J. L. (2011). Behaviour of the motoneurone pool in a fatiguing submaximal contraction. *Journal of Physiology, 589*(Pt 14), 3533-3544. https://doi.org/10.1113/jphysiol.2011.207191

Messier, S. P. (1982). *Relationships among selected kinetic parameters, bat velocities, and three methods of striding by female softball batters.* Temple University].

Mihoces, G. (2003, March 3, 2003). 10 hardest things to do in sports: Part III. *USA Today,* 3C. https://www.yumpu.com/en/document/read/43030531/10-hardest-things-to-do-in-sports-part-iii-usa-today-education-

Miller, R. M., & Bemben, M. G. (2017). Lower limb muscular power and its relationship to hitting performance measures in collegiate baseball and softball athletes. *Journal of Sport and Human Performance, 5*(2). https://doi.org/10.12922/jshp.v5i2.118

Millet, G. Y., & Lepers, R. (2004). Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. *Sports Medicine, 34*(2), 105-116.

Minetos, P. D., Trojan, J. D., Brown, S. M., & Mulcahey, M. K. (2020). Softball pitching mechanics and shoulder injuries: a narrative review. *Sports Biomech*, 1-13. https://doi.org/10.1080/14763141.2020.1757142

Mullaney, M. J., McHugh, M. P., Donofrio, T. M., & Nicholas, S. J. (2005). Upper and lower extremity muscle fatigue after a baseball pitching performance. *The American Journal of Sports Medicine, 33*(1), 108-113. https://doi.org/0.1177/0363546504266071

Murphy, A. P., Duffield, R., Kellett, A., & Reid, M. (2016). A comparison of the perceptual and technical demands of tennis training, simulated match play, and competitive tournaments. *International Journal of Sports Physiology and Performance, 11*(1), 40-47. https://doi.org/10.1123/ijspp.2014-0464

Murray, T. A., Cook, T. D., Werner, S. L., Schlegel, T. F., & Hawkins, R. J. (2001). The effects of extended play on professional baseball pitchers. *The American Journal of Sports Medicine, 29*(2), 137-142.

Nakata, H., Miura, A., Yoshie, M., & Kudo, K. (2012). Differences in the head movement during baseball batting between skilled players and novices. *Journal of Strength and Conditioning Research, 26*(10), 2632-2640.

Nimphius, S. (2011a). Monitoring neuromuscular fatigue in amateur baseball players during a national tournament. *Journal of Australian Strength and Conditioning, 19*(S1), 110-114.

Nimphius, S. (2011b). Upper body strength and power characteristics in female fastpitch athletes. *Journal of Strength and Conditioning Research, 25*(1), S90-S91.

Nimphius, S., McGuigan, M. R., & Newton, R. U. (2010). Relationship between strength, power, speed, and change of direction performance of female softball players. *Journal of Strength and Conditioning Research, 24*(4), 885-895.

Nimphius, S., McGuigan, M. R., & Newton, R. U. (2012). Changes in muscle architecture and performance during a competitive season in female softball players. *Journal of Strength and Conditioning Research, 26*(10), 2655-2666.

Nimphius, S., McGuigan, M. R., Suchomel, T. J., & Newton, R. U. (2016). Variability of a "force signature" during windmill softball pitching and relationship between discrete force variables and pitch velocity. *Hum Mov Sci, 47*, 151-158. https://doi.org/10.1016/j.humov.2016.03.005

O'Brien, J., Santner, E., & Finch, C. F. (2018). The inter-tester reliability of the squeeze and bent-knee-fall-out tests in elite academy football players. *Physical Therapy in Sport, 34*, 8-13. https://doi.org/10.1016/j.ptsp.2018.08.004

O'Brien, M., Bourne, M., Heerey, J., Timmins, R. G., & Pizzari, T. (2019). A novel device to assess hip strength: Concurrent validity and normative values in male athletes. *Physical Therapy in Sport 35*, 63-68. https://doi.org/10.1016/j.ptsp.2018.11.006

Ojala, T., & Häkkinen, K. (2013). Effects of tennis tournament on players' physical performance, hormonal responses, muscle damage and recovery. *Journal of Sports Science & Medicine, 12*, 240-248.

Oliver, G. D. (2014). Relationship between gluteal muscle activation and upper extremity kinematics and kinetics in softball position players. *Medical and Biological Engineering and Computing, 52*(3), 265-270. https://doi.org/10.1007/s11517-013-1056-3

Oliver, G. D., & Keeley, D. W. (2010). Gluteal muscle group activation and its relationship with pelvis and torso kinematics in high-school baseball pitchers. *Journal of Strength and Conditioning Research, 24*(11), 3015-3022.

Oliver, G. D., & Plummer, H. (2011). Ground reaction forces, kinematics, and muscle activations during the windmill softball pitch. *Journal of Sports Sciences, 29*(10), 1071-1077. https://doi.org/0.1080/02640414.2011.576692

Oliver, G. D., Plummer, H. A., Washington, J., Weimar, W. H., & Brambeck, A. (2019). Effects of game performance on softball pitchers and catchers. *Journal of Strength and Conditioning Research, 33*(2). https://doi.org/10.1519/JSC.0000000000001848

Oliver, G. D., Washington, J., Gascon, S. S., Plummer, H., Escamilla, R. F., & Andrews, J. R. (2019). Effects of hip abduction fatigue on trunk and shoulder kinematics during throwing and passive hip rotational range of motion. *Journal of Sports Rehabilitation, 28*, 304-310. https://doi.org/10.1123/jsr.2017-0182

Pageaux, B., & Lepers, R. (2018). The effects of mental fatigue on sport-related performance. *Progress in Brain Research, 240*, 291-315. https://doi.org/10.1016/bs.pbr.2018.10.004

Patel, N., Bhatia, A., Mullen, C., Bosman, E., & Lear, A. (2021). Professional women's softball injuries: An epidemiological cohort study. *Clinical Journal of Sport Medicine, 31*(1), 63-69. https://doi.org/10.1097/JSM.0000000000000698

Paul, D. J., Nassis, G. P., Whiteley, R., Marques, J. B., Kenneally, D., & Chalabi, H. (2014). Acute responses of soccer match play on hip strength and flexibility measures: potential measure of injury risk. *Journal of Sports Sciences, 32*(13), 1318-1323. https://doi.org/10.1080/02640414.2014.927069

Peart, A., Wadsworth, D., Washington, J., & Oliver, G. (2018). Body composition assessment in female national collegiate athletic association division I softball athletes as a function of playing position across a multiyear time frame. *Journal of Strength and Conditioning Research*.

Petersen, C., Pyne, D., Portus, M., & Dawson, B. (2009). Validity and reliability of GPS units to monitor cricket-specific movement patterns. *International Journal of Sports Physiology and Performance, 4*, 381-393.

Petersen, C. J., Pyne, D., Dawson, B., Kellett, A., & Portus, M. (2011). Comparison of training and game demands of national level cricketers. *Journal of Strength and Conditioning Research, 25*(5), 1306-1311.

Petersen, C. J., Pyne, D., Dawson, B., Portus, M., & Kellett, A. (2010). Movement patterns in cricket vary by both position and game format. *Journal of Sports Sciences, 28*(1), 45-52. https://doi.org/10.1080/02640410903348665

Phinyomark, A., Thongpanja, S., Hu, H., Phukpattaranont, P., & Limsakul, C. (2012). The usefulness of mean and median frequencies in electromyography analysis. In *Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges*. https://doi.org/10.5772/50639

Pincivero, D. M., Campy, R. M., Salfetnikov, Y., Bright, A., & Coelho, A. J. (2001). Influence of contraction intensity, muscle, and gender on median frequency of the quadriceps femoris. *Journal of Applied Physiology, 90*, 804-810.

Pinniger, G. J., Steele, J. R., & Groeller, H. (2000). Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine and Science in Sports and Exercise, 32*(3), 647-653.

Plummer, H. A., & Oliver, G. D. (2014). The relationship between gluteal muscle activation and throwing kinematics in baseball and softball catchers. *Journal of Strength and Conditioning Research, 28*(1), 87-96.

Reilly, T., Morris, T., & Whyte, G. (2009). The specificity of training prescription and physiological assessment: A review. *Journal of Sports Sciences, 27*(6), 575-589. https://doi.org/10.1080/02640410902729741

Reilly-Boccia, C., Ficklin, T., Lund, R., Horvas, J., & Beatty, K. (2015). Bat quickness and bat velocity in Division I softball players. *Sport Journal*, 7-7.

Remaley, D. T., Fincham, B., McCullough, B., Davis, K., Nofsinger, C., Armstrong, C., & Stausmire, J. M. (2015). Surface electromyography of the forearm musculature during the windmill softball pitch. *Orthopaedic Journal of Sports Medicine, 3*(1). https://doi.org/10.1177/2325967114566796

Reyes, G. F. C., & Dolny, D. (2009). Acute effects of various weighted bat warm-up protocls on bat velocity. *Journal of Strength and Conditioning Research, 23*(7), 2114-2118.

Roe, G., Darrall-Jones, J., Till, K., Phibbs, P., Read, D., Weakley, J., & Jones, B. (2016). Between-days reliability and sensitivity of common fatigue measures in rugby players. *International Journal of Sports Physiology and Performance, 11*(5), 581-586. https://doi.org/10.1123/ijspp.2015-0413

Roe, G., Phibbs, P. J., Till, K., Jones, B. L., Read, D. B., Weakley, J. J., & Darrall-Jones, J. D. (2016). Changes in adductor strength after competition in academy rugby union players. *Journal of Strength and Conditioning Research, 30*(2), 344-350.

Rojas, I. L., Provencher, M. T., Bhatia, S., Foucher, K. C., Bach, B. R., Jr., Romeo, A. A., Wimmer, M. A., & Verma, N. N. (2009). Biceps activity during windmill softball pitching: Injury implications and comparison with overhand throwing. *American Journal of Sports Medicine, 37*(3), 558-565. https://doi.org/10.1177/0363546508328105

Roman-Liu, D. (2016). The influence of confounding factors on the relationship between muscle contraction level and MF and MPF values of EMG signal: a review. *International Journal of Occupational Safety and Ergonomics, 22*(1), 77-91. https://doi.org/10.1080/10803548.2015.1116817

Ronglan, L. T., Raastad, T., & Børgesen, A. (2006). Neuromuscular fatigue and recovery in elite female handball players. *Scandinavian Journal of Medicine and Science in Sports, 16*, 267-273. https://doi.org/10.1111/j.1600-0838.2005.00474.x

Rubinstein, S., & Kamen, G. (2005). Decreases in motor unit firing rate during sustained maximal-effort contractions in young and older adults. *Journal of Electromyography and Kinesiology, 15*(6), 536-543. https://doi.org/10.1016/j.jelekin.2005.04.001

Rudkin, S. T., & O'Donoghue, P. G. (2008). Time-motion analysis of first-class cricket fielding. *Journal of Science and Medicine in Sport, 11*(6), 604-607. https://doi.org/10.1016/j.jsams.2007.08.004

Ryan, S., Kempton, T., Pacecca, E., & Coutts, A. J. (2018). Measurement properties of an adductor strength assessment system in professional Australian footballers. *International Journal of Sports Physiology and Performance*, 1-13. https://doi.org/10.1123/ijspp.2018-0264

Ryan, S., Pacecca, E., Tebble, J., Hocking, J., Kempton, T., & Coutts, A. J. (2019). Measurement characteristics of athlete monitoring tools in professional Australian football. *International Journal of Sports Physiology and Performance, 15*, 457-463. https://doi.org/10.1123/ijspp.2019-0060

Shaffer, B., Jobe, F. W., Pink, M. M., & Perry, J. (1993). Baseball batting- An electromyographic study. *Clinical Orthopaedics and Related Research, 292*, 285-293.

Skillington, S. A., Brophy, R. H., Wright, R. W., & Smith, M. V. (2017). Effect of pitching consecutive days in youth fast-pitch softball tournaments on objective shoulder strength and subjective shoulder symptoms. *The American Journal of Sports Medicine, 45*(6), 1413-1419. https://doi.org/0.1177/0363546516688657

Sleivert, G. G., & Wenger, H. A. Reliability of measuring isometric and isokinetic peak torque, rate of torque development, integrated electromyography, and tibial nerve conduction velocity. *Archives of Physical Medicine and Rehabilitation, 75*(12), 1315-1321. https://doi.org/10.5555/uri:pii:0003999394902798

Smith, J. L., Martin, P. G., Gandevia, S. C., & Taylor, J. L. (2007). Sustained contraction at very low forces produces prominent supraspinal fatigue in human elbow flexor muscles. *Journal of Applied Physiology, 103*(2), 560-568. https://doi.org/10.1152/japplphysiol.00220.2007

Smith, M. R., Fransen, J., Deprez, D., Lenoir, M., & Coutts, A. J. (2016). Impact of mental fatigue on speed and accuracy components of soccer-specific skills. *Science and Medicine in Football, 1*(1), 48-52. https://doi.org/10.1080/02640414.2016.1252850

Smith, M. R., Marcora, S. M., & Coutts, A. J. (2015). Mental fatigue impairs intermittent running performance. *Medicine and Science in Sport and Exercise, 47*(8), 1682-1690. https://doi.org/10.1249/MSS.0000000000000592

Softball Australia Archived Events. (n.d.). Retrieved 30/3/18 from http://www.softball.org.au/2016-events/

Softball Olympic Games 2021 Schedule. (2020, 1/2/21). Retrieved 1/31/2021 from https://olympicsoftball.wbsc.org/en/2021/e-2021-softball-olympic-games/schedule-and-results

Sparto, P. J., Parnianpour, M., Reinsel, T. E., & Simon, S. (1997). The effect of fatigue on multijoint kinematics, coordination, and postural stability during a repetitive lifting test. *Journal of Orthopaedic and Sports Physical Therapy, 25*(1), 3-12.

Spencer, M., Lawrence, S., Rechichi, C., Bishop, D., Dawson, B., & Goodman, C. (2004). Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. *Journal of Sports Sciences, 22*(9), 843-850. https://doi.org/10.1080/02640410410001716715

Spencer, M., Rechichi, C., Lawrence, S., Dawson, B., Bishop, D., & Goodman, C. (2005). Time-motion analysis of elite field hockey during several games in succession: A tournament scenario. *Journal of Science and Medicine in Sport, 8*(4), 382-391.

St Clair Gibson, A., Lambert, M. I., & Noakes, T. D. (2001). Neural control of force output during maximal and submaximal exercise. *Sports Medicine, 31*(9), 637-650.

Stergiou, N., & Decker, L. M. (2011). Human movement variability, nonlinear dynamics, and pathology: Is there a connection? *Hum Mov Sci, 30*(5), 869-888. https://doi.org/10.1016/j.humov.2011.06.002

Stratford, P. W., & Balsor, B. E. (1994). A comparison of make and break tests using a hand-held dynamometer and the Kin-Com. *Journal of Orthopaedic and Sports Physical Therapy, 19*(1), 28-32. https://doi.org/10.2519/jospt.1994.19.1.28

Stulen, F. B., & De Luca, C. J. (1981). Frequency parameters of the myoelectric signal as a measure of muscle conduction velocity. *IEEE Transactions on Biomedical Engineering, BME-28*(7), 515-523. https://doi.org/10.1109/TBME.1981.324738

Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Medicine, 46*(10), 1419-1449. https://doi.org/10.1007/s40279-016-0486-0

Szymanski, D. J., DeRenne, C., & Spaniol, F. J. (2009). Contributing factors for increased bat swing velocity. *Journal of Strength and Conditioning Research, 23*(4), 1338-1352.

Tallent, J., Higgins, M. F., Parker, N., Waldron, M., Bradford, E., Keenan, J., & O'Neill, B. V. (2017). Quantification of bowling workload and changes in cognitive function in elite fast bowlers in training compared with Twenty20 cricket. *The Journal of Sports Medicine and Physical Fitness, 59*(1), 35-41. https://doi.org/10.23736/S0022-4707.17.07940-3

Taylor, J. L., Amann, M., Duchateau, J., Meeusen, R., & Rice, C. L. (2016). Neural contributions to muscle fatigue: From the brain to the muscle and back again. *Medicine and Science in Sport and Exercise, 48*(11), 2294-2306. https://doi.org/10.1249/MSS.0000000000000923

Taylor, J. L., & Gandevia, S. C. (2008). A comparison of central aspects of fatigue in submaximal and maximal voluntary contractions. *J Appl Physiol (1985), 104*(2), 542-550. https://doi.org/10.1152/japplphysiol.01053.2007

Taylor, J. L., Todd, G., & Gandevia, S. C. (2006). Evidence for a supraspinal contribution to human muscle fatigue. *Clinical and Experimental Pharmacology and Physiology, 33*, 400-405.

Taylor, K.-L., Chapman, D. W., Cronin, J. B., Newton, M. J., & Gill, N. (2012). Fatigue monitoring in high performance sport: A survey of current trends. *Journal of Australian Strength and Conditioning, 20*(1), 12-23.

Teichler, L. S. (2010). *The relationship between bat velocity, upper and lower extremity power and the rotational kinetic chain in NCAA Division II softball players* Western Washington University]. WWU Graduate School Collection. https://cedar.wwu.edu/wwuet/61

Terbizan, D. J., Waldera, M., Seljevold, P., & Schweigert, D. J. (1996). Physiological characteristics of masters women fastpitch softball players. *Journal of Strength and Conditioning Research, 10*(3), 157-160.

Thomas, K., Goodall, S., Stone, M., Howatson, G., St Clair Gibson, A., & Ansley, L. (2015). Central and peripheral fatigue in male cyclists after 4-, 20-, and 40-km time trials. *Medicine and Science in Sports and Exercise, 47*(3), 537-546. https://doi.org/10.1249/MSS.0000000000000448

Thompson, D., Nicholas, C. W., & Williams, C. (1999). Muscular soreness following prolonged intermittent high-intensity shuttle running. *Journal of Sports Sciences, 17*(5), 387-395. https://doi.org/10.1080/026404199365902

Thorborg, K., Serner, A., Petersen, J., Moller Madsen, T., Magnusson, P., & Holmich, P. (2011). Hip adduction and abduction strength profiles in elite soccer players: Implications for clinical evaluations of hip adductor muscle recovery after injury. *The American Journal of Sports Medicine, 39*(1), 121-126.

Till, M. E., Bassett, K. E., Beiser, E. J., Medlin, G. L., Szymanski, J. M., Brooks, K. A., & Szymanski, D. J. (2011). Relationship between lower body power, body mass, and softball-specific skills. *Journal of Strength and Conditioning Research, 25*, S65-S66.

Tripp, B. L., Yochem, E. M., & Uhl, T. L. (2007). Functional fatigue and upper extremity sensorimotor system acuity in baseball athletes. *Journal of Athletic Training, 42*(1), 90-98.

Tyler, T. F., Nicholas, S. J., Campbell, R. J., & McHugh, M. P. (2001). The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. *The American Journal of Sports Medicine, 29*(2), 124-128.

Veness, D., Patterson, S. D., Jeffries, O., & Waldron, M. (2017). The effects of mental fatigue on cricket-relevant performance among elite players. *Journal of Sports Sciences, 35*(24), 2461-2467. https://doi.org/10.1080/02640414.2016.1273540

Vickery, W., Duffield, R., Crowther, R., Beakley, D., Blanch, P. D., & Dascombe, B. J. (2018). Comparison of the physical and technical demands of cricket players during training and match-play. *Journal of Strength and Conditioning Research, 32*(3), 821-829. https://doi.org/10.1519/JSC.0000000000001528

Viitasalo, J. H. T., & Komi, P. V. (2008). Signal characteristics of emg with special reference to reproducibility of measurements. *Acta Physiologica Scandinavica, 93*(4), 531-539. https://doi.org/10.1111/j.1748-1716.1975.tb05845.x

Virr, J. L., Game, A., Bell, G. J., & Syrotuik, D. (2014). Physiological demands of women's rugby union: Time-motion analysis and heart rate response. *Journal of Sports Sciences, 32*(3), 239-247. https://doi.org/10.1080/02640414.2013.823220

Wadsworth, C., Nielsen, D. H., Corcoran, D. S., Phillips, C. E., & Sannes, T. L. (1992). Interrater reliability of hand-held dynamometry: effects of rater gender, body weight, and grip strength. *The Journal Of Orthopaedic And Sports Physical Therapy, 16*(2), 74-81. http://ezproxy.ecu.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=18780994&site=ehost-live&scope=site

Wagner, H., Pfusterschmied, J., Klous, M., von Duvillard, S. P., & Muller, E. (2012). Movement variability and skill level of various throwing techniques. *Hum Mov Sci, 31*(1), 78-90. https://doi.org/10.1016/j.humov.2011.05.005

Waqar, A., Ahmad, I., Habibi, D., & Phung, Q. V. (2021). Analysis of GPS and UWB positioning system for athlete tracking. *Measurement: Sensors, 14*. https://doi.org/10.1016/j.measen.2020.100036

Washington, J. (2018). *Influence of the lumbopelvic-hip complex on female softball hitting* Auburn University]. Auburn University Electronic Thesis Database. http://hdl.handle.net/10415/6222

Washington, J., Gilmer, G., & Oliver, G. (2018). Acute hip abduction fatigue on lumbopelvic-hip complex stability in softball players. *International Journal of Sports Medicine, 39*(7), 571-575. https://doi.org/10.1055/a-0577-3722

Washington, J., & Oliver, G. (2018). Kinematic differences between hitting off a tee versus front toss in collegiate softball players. *International Biomechanics, 5*(1), 30-35. https://doi.org/10.1080/23335432.2018.1472038

Weimer, B., Halet, K., & Anderson, T. (2007). Relationship of strength variables to bat velocity in college baseball and softball players. *Missouri Journal of Health, Physical Education, Recreation and Dance, 17*, 53-59.

Welch, C. M., Banks, S. A., Cook, F. F., & Draovitch, P. (1995). Hitting a baseball: A biomechanical description. *Journal of Orthopaedic and Sports Physical Therapy, 22*(5), 193-201.

Werner, S. L., Jones, D. G., Guido, J. A., & Brunet, M. E. (2017). Kinematics and kinetics of elite windmill softball pitching. *The American Journal of Sports Medicine, 34*(4), 597-603. https://doi.org/10.1177/0363546505281796

Wikholm, J. B., & Bohannon, R. W. (1991). Hand-held dynamometer measurements: Tester strength makes a difference. *The Journal Of Orthopaedic And Sports Physical Therapy, 13*(4), 191-198. http://ezproxy.ecu.edu.au/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=18796845&site=ehost-live&scope=site

Williams, T., & Underwood, J. (1986). *The science of hitting*. Simon & Schuster.

Wisbey, B., Montgomery, P. G., Pyne, D. B., & Rattray, B. (2010). Quantifying movement demands of AFL football using GPS tracking. *Journal of Science and Medicine in Sport, 13*(5), 531-536. https://doi.org/10.1016/j.jsams.2009.09.002

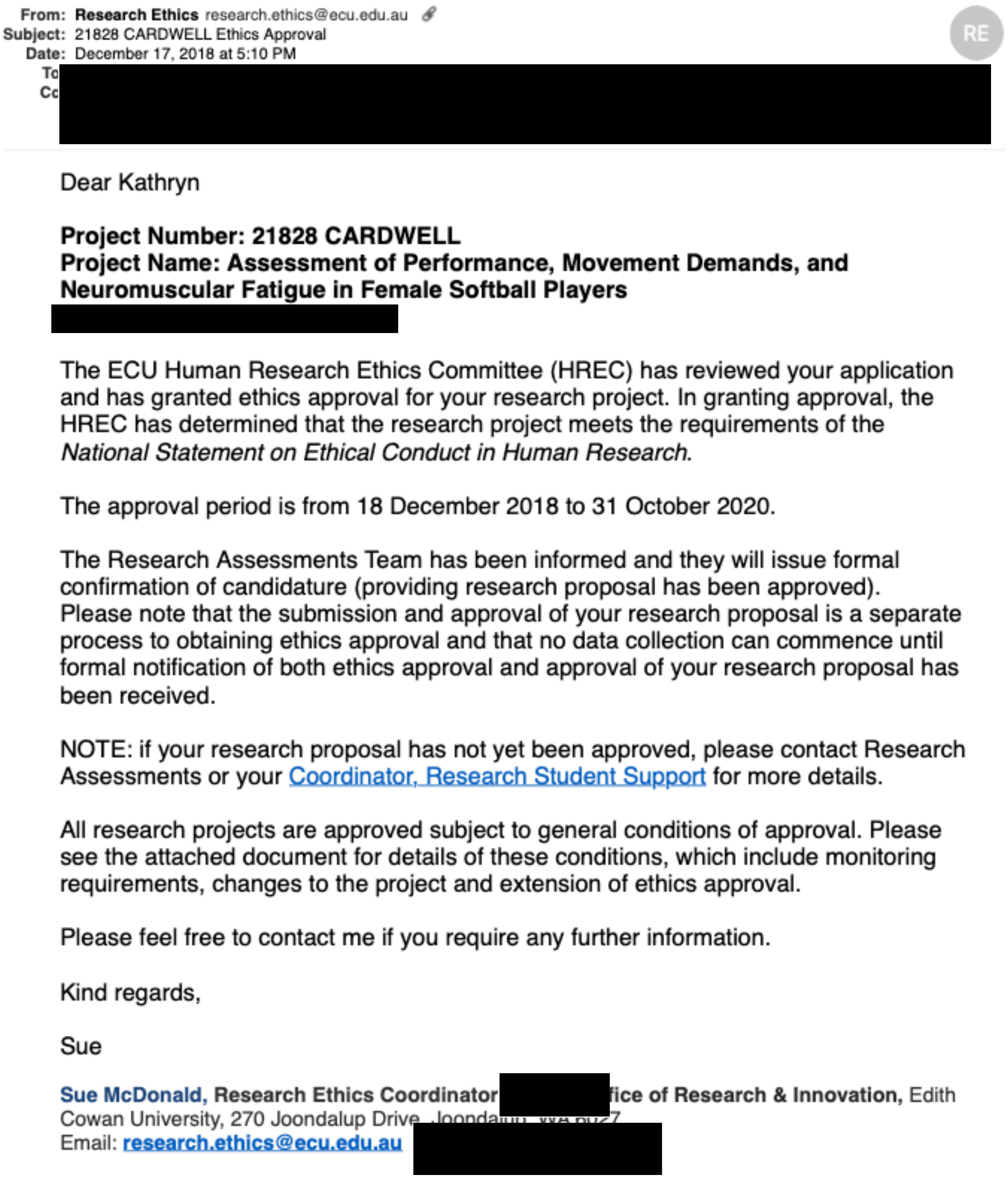
Wollin, M., Pizzari, T., Spagnolo, K., Welvaert, M., & Thorborg, K. (2018). The effects of football match congestion in an international tournament on hip adductor squeeze strength and pain in elite youth players. *Journal of Sports Sciences, 36*(10), 1167-1172. https://doi.org/10.1080/02640414.2017.1363452

Wollin, M., Thorborg, K., Welvaert, M., & Pizzari, T. (2018). In-season monitoring of hip and groin strength, health and function in elite youth soccer: Implementing an early detection and management strategy over two consecutive seasons. *Journal of Science and Medicine in Sport, 21*(10), 988-993. https://doi.org/10.1016/j.jsams.2018.03.004

World Baseball Softball Confederation. (2017). *Report: Baseball/Softball top list as most participated team sport in U.S.* Retrieved January 19, 2018 from http://www.wbsc.org/news/report-baseballsoftball-top-list-as-most-participated-team-sport-in-u-s/

APPENDIX A

Proof of Ethics



From: **Research Ethics** research.ethics@ecu.edu.au
Subject: 21828 CARDWELL Ethics Approval
Date: December 17, 2018 at 5:10 PM
Tc
Cc [redacted]

Dear Kathryn

Project Number: 21828 CARDWELL
Project Name: Assessment of Performance, Movement Demands, and Neuromuscular Fatigue in Female Softball Players
[redacted]

The ECU Human Research Ethics Committee (HREC) has reviewed your application and has granted ethics approval for your research project. In granting approval, the HREC has determined that the research project meets the requirements of the *National Statement on Ethical Conduct in Human Research*.

The approval period is from 18 December 2018 to 31 October 2020.

The Research Assessments Team has been informed and they will issue formal confirmation of candidature (providing research proposal has been approved). Please note that the submission and approval of your research proposal is a separate process to obtaining ethics approval and that no data collection can commence until formal notification of both ethics approval and approval of your research proposal has been received.

NOTE: if your research proposal has not yet been approved, please contact Research Assessments or your Coordinator, Research Student Support for more details.

All research projects are approved subject to general conditions of approval. Please see the attached document for details of these conditions, which include monitoring requirements, changes to the project and extension of ethics approval.

Please feel free to contact me if you require any further information.

Kind regards,

Sue

Sue McDonald, Research Ethics Coordinator [redacted] **fice of Research & Innovation,** Edith Cowan University, 270 Joondalup Drive [redacted]
Email: **research.ethics@ecu.edu.au**

APPENDIX B

Standardised Warm-up For Chapter 5

- Yoga Push-up x 5
- Scorpion x 5
- Lying Trunk Rotations x 5
- Inchworm - 10 m
- Lunges with Shoulder Rotation - 10 m
- Walking Backwards – 10 m
- Lateral Skips with Arm Swings – 10 m
- Catcher Lunges – 10 m
- Walking Quads with Calf Raises – 10 m
- Walking Hamstrings with Toe Up – 10 m
- Walking External Hip Rotations – 10 m
- Knee Hugs – 10 m
- Walking Hamstring Stretch – 10 m
- Carioca – 10 m x 2

APPENDIX C

Study 1 RStudio Code

Frequency data

```
library(dplyr)
library(tidyr)
library(ggplot2)

Day_7_SA_SS <- read.delim("~/TMA Study/SS/Day 7 SA SS Timecode.csv",
            sep = ",",
             colClasses = c("character", "character", "character", "NULL", "NULL", "NULL"))

data2 <- Day_7_SA_SS %>%
  mutate_at(c("category"), factor) %>%  # convert category into a categorical variable
  separate(start.time, c("Start.Hour", "Start.Min", "Start.Sec", "Start.cSec")) %>%   # split start.time into four columns
  separate(end.time, c("End.Hour", "End.Min", "End.Sec", "End.cSec")) %>%   # split End.Time into four
mutate(start_csec = 60*60*100*as.numeric(Start.Hour) +  # new column = scaling/adding of component columns
       60*100*as.numeric(Start.Min) +
       100*as.numeric(Start.Sec) +
       as.numeric(Start.cSec),
     end_csec = 60*60*100*as.numeric(End.Hour) +
       60*100*as.numeric(End.Min) +
       100*as.numeric(End.Sec) +
       as.numeric(End.cSec)) %>%
  mutate(duration_csec = end_csec - start_csec) %>%   # new duration column = end - start times
  dplyr::select(category, start_csec, end_csec, duration_csec)   # just retain these four columns

fielding_times <- data2 %>%
```

```
  filter(category %in% c("Flames Field", "Between Innings"))

for (ff in 1:nrow(fielding_times)) {
  data2$fielding_session[data2$start_csec >= fielding_times$start_csec[ff] &
                         data2$end_csec <= fielding_times$end_csec[ff]] <- ff
}

FS_BI <- data2 %>%
  select(fielding_session, category) %>%
  filter(category == "Between Innings") %>%
  distinct(fielding_session) %>%
  pull(fielding_session)

FS_FF <- data2 %>%
  select(fielding_session, category) %>%
  filter(category == "Flames Field") %>%
  distinct(fielding_session) %>%
  pull(fielding_session)

BI <- data2 %>%
  filter(fielding_session %in% FS_BI) %>%
  group_by(category) %>%
  summarise(total_duration_sec = (sum(duration_csec)/100))

FF <- data2 %>%
  filter(fielding_session %in% FS_FF) %>%
  group_by(category) %>%
  summarise(total_duration_sec = (sum(duration_csec)/100))

write.table(FF, file = "Day_7_SA_SS_FF.csv", sep = ",", row.names = FALSE)

write.table(BI, file = "Day_7_SA_SS_BI.csv", sep = ",", row.names = FALSE)
```

Sprint Duration Data

```
library(dplyr)
library(tidyr)
library(ggplot2)

Day_3_QLD_RF <- read.delim("~/TMA Study/RF/Day 3 QLD RF Timecode.csv",
                           sep = ",",
                           colClasses = c("character", "character", "character", "NULL", "NULL",
"NULL"))

data2 <- Day_3_QLD_RF %>%
  mutate_at(c("category"), factor) %>%  # convert category into a categorical variable
  separate(start.time, c("Start.Hour", "Start.Min", "Start.Sec", "Start.cSec")) %>%   # split
start.time into four columns
  separate(end.time, c("End.Hour", "End.Min", "End.Sec", "End.cSec")) %>%    # split
End.Time into four
  mutate(start_csec = 60*60*100*as.numeric(Start.Hour) +  # new column = scaling/adding of
component columns
         60*100*as.numeric(Start.Min) +
         100*as.numeric(Start.Sec) +
         as.numeric(Start.cSec),
        end_csec = 60*60*100*as.numeric(End.Hour) +
         60*100*as.numeric(End.Min) +
         100*as.numeric(End.Sec) +
         as.numeric(End.cSec)) %>%
  mutate(duration_csec = end_csec - start_csec) %>%   # new duration column = end - start
times
  dplyr::select(category, start_csec, end_csec, duration_csec)   # just retain these four columns

Sprints <- data2 %>%
  filter(category %in% c("Live Sprinting"))

write.table(Sprints, file = "~/Desktop/Sprints/Day_3_QLD_RF_Sprints.csv", sep = ",",
row.names = FALSE)
```

Batting Data

```
library(dplyr)
library(tidyr)
library(ggplot2)

Day_4_SA_XXXXX <- read.delim("~/TMA Study/XXXXX/Day 4 SA XXXXX
Timecode.csv",
                colClasses = c("character", "character", "character", "NULL", "NULL",
"NULL"))

data2 <- Day_4_SA_XXXXX %>%
  mutate_at(c("category"), factor) %>%  # convert category into a categorical variable
  separate(start.time, c("Start.Hour", "Start.Min", "Start.Sec", "Start.cSec")) %>%   # split
start.time into four columns
  separate(end.time, c("End.Hour", "End.Min", "End.Sec", "End.cSec")) %>%   # split
End.Time into four
mutate(start_csec = 60*60*100*as.numeric(Start.Hour) +  # new column = scaling/adding of
component columns
        60*100*as.numeric(Start.Min) +
        100*as.numeric(Start.Sec) +
        as.numeric(Start.cSec),
      end_csec = 60*60*100*as.numeric(End.Hour) +
        60*100*as.numeric(End.Min) +
        100*as.numeric(End.Sec) +
        as.numeric(End.cSec)) %>%
  mutate(duration_csec = end_csec - start_csec) %>%   # new duration column = end - start
times
  dplyr::select(category, start_csec, end_csec, duration_csec)   # just retain these four columns

batting_times <- data2 %>%
  filter(category %in% c("Flames Bat"))
```

```
for (ff in 1:nrow(batting_times)) {
  data2$batting_session[data2$start_csec >= batting_times$start_csec[ff] &
                          data2$end_csec <= batting_times$end_csec[ff]] <- ff
}

FS_FF <- data2 %>%
  select(batting_session, category) %>%
  filter(category == "Flames Bat") %>%
  distinct(batting_session) %>%
  pull(batting_session)

FF <- data2 %>%
  filter(batting_session %in% FS_FF) %>%
  group_by(category) %>%
  summarise(total_duration_sec = (sum(duration_csec)/100))

write.table(FF, file = "~/Desktop/Batting/XXXXX/Day_4_SA_XXXXX.csv", sep = ",",
row.names = FALSE)

Sprints <- data2 %>%
  filter(category %in% c("Live Sprinting"))

write.table(Sprints, file = "~/Desktop/Batting/Sprint/Day_4_SA_XXXXX_Sprint.csv", sep =
",", row.names = FALSE)
```

APPENDIX D

Study 4 RStudio Code

```
library(dplyr)
library(tidyr)
library(ggplot2)
library(lmerTest)
library(readxl)
library(multcomp)
library(effects)


demographic_data <- read_excel("Study 4 Data_stripped.xlsx",
                    sheet = "Demographics",
                    col_names = c("Player", "Weight", "Height", "Age"),
                    skip = 1,
                    trim_ws = TRUE)


practice_data_wide <- read_excel("Study 4 Data_stripped.xlsx",
                     sheet = "Practice",
                     skip = 3,
                     col_names = c("Player", "Pre.Abduction.Left", "Pre.Abduction.Right",
"Pre.Adduction.Left", "Pre.Adduction.Right","Post.Abduction.Left", "Post.Abduction.Right",
"Post.Adduction.Left", "Post.Adduction.Right", "Play.Time"))
practice_data_wide


game_data_wide <- read_excel("Study 4 Data_stripped.xlsx",
                  sheet = "Game",
                  skip = 3,
                  col_names = c("Player", "Pre.Abduction.Left", "Pre.Abduction.Right",
"Pre.Adduction.Left", "Pre.Adduction.Right","Post.Abduction.Left", "Post.Abduction.Right",
"Post.Adduction.Left", "Post.Adduction.Right", "Play.Time"))
```

```
game_data_wide

practice_data <- practice_data_wide %>%
  pivot_longer(Pre.Abduction.Left:Post.Adduction.Right,  # the columns we want to make tall
            values_to = "Force",  # new column that will hold what were previously column names
            names_to = "Variable")  # new column to store the values from the cells in the old columns.
practice_data

game_data <- game_data_wide %>%
  pivot_longer(Pre.Abduction.Left:Post.Adduction.Right,  # the columns we want to make tall
            values_to = "Force",  # new column that will hold what were previously column names
            names_to = "Variable")  # new column to store the values from the cells in the old columns.
game_data

practice_data <- practice_data %>%
  separate(Variable, c("Timepoint", "Action", "Side")) %>%
  mutate_at(c("Player", "Action", "Side"), as.factor) %>%
  mutate_at("Timepoint", factor, levels = c("Pre", "Post"))
practice_data

game_data <- game_data %>%
  separate(Variable, c("Timepoint", "Action", "Side")) %>%
  mutate_at(c("Player", "Action", "Side"), as.factor) %>%
  mutate_at("Timepoint", factor, levels = c("Pre", "Post"))
game_data

all_data <- bind_rows("Practice" = practice_data, "Game" = game_data, .id = "Setting")
```

```
model_lmm <- lmer(Force ~ Timepoint*Setting + Action + (1|Player/Side), data = all_data)

summary(model_lmm)


e <- allEffects(model_lmm)
e
plot(e)

coef(model_lmm)

confint(model_lmm, level = 0.95)

Resid_model_lmm <- residuals(model_lmm)
Resid_abs_model_lmm <- abs(Resid_model_lmm)
Resid_model_lmm2 <- Resid_abs_model_lmm^2
```