THE BIOMECHANICAL, PHYSIOLOGICAL AND RECOVERY RESPONSE TO THE EXTRA-TIME PERIOD OF MALE SOCCER

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Thesis submitted to the University of Huddersfield in partial fulfilment of the degree of Doctor of Philosophy

Research undertaken in the School of Human and Health Sciences

The University of Huddersfield

2021

ABSTRACT

Soccer matches are traditionally contested over 90 min. However, when matches are tied in the knockout-phase of some major tournaments, there is an additional 30 min extra-time (ET) period. Aspects of ET have been investigated but knowledge of the biomechanical, physiological and recovery responses to ET is limited. The overarching aim of this thesis was to assess the biomechanical, physiological and recovery responses to 120-minutes of soccer-specific exercise. The specific objectives were to *i)* review the ET literature and identify gaps in knowledge, *ii)* evaluate the reliability of a 120-min treadmill-based soccer-specific exercise protocol, *iii*) investigate the physiological and *iv*) biomechanical responses to 120-min of soccer-specific exercise, *v)* explore practitioner views and practices on recovery following ET matches, and *vi)* assess the recovery responses following 120-min of soccer-specific exercise. To identify gaps in the literature, a systematic review of the ET period of soccer was conducted. The systematic review revealed a dearth of robust evidence concerning biomechanical measures, direct assessments of substrate utilisation, and controlled recovery assessments, during and following 120-min of soccer-specific exercise. The original contribution to new knowledge relates to the critical and systematic appraisal of current ET literature and investigations that explore under researched facets of ET, including biomechanical, physiological and recovery responses.

The four studies of the thesis are distinct in scope but integrate to form a series of studies that are common in their approach to evolving understanding of the ET period of soccer. Study one assessed the test-retest reliability of a validated soccer-specific exercise protocol. The protocol demonstrated moderate-to-very strong reliability. PlayerLoad™, respiratory exchange ratio (RER), and differential ratings of perceived exertion (d-RPE) were also assessed in the study. PlayerLoad™ and d-RPE values increased during ET, and a shift towards fat oxidation was observed during this additional 30-min period. For study two, lower-limb muscle excitation and peak torque responses were assessed over 120-min of soccer-specific activity. Muscle excitation of the rectus femoris was reduced during ET, and decrements in eccentric peak torque of the knee flexors were observed post 120 min versus pre-exercise. Study three surveyed practitioners' perceptions and practices related to player recovery following ET. Most practitioners specified that competing in 120 min of match-play delays the time-course of recovery (88%), that practices should be adapted following ET matches (82%) and promote further research on recovery following this additional 30 min period (88%). For study four, recovery was assessed following 90- and 120-min of soccer-specific activity. Creatine kinase activity was higher following the 120 min trial, but functional and perceptual recovery measures were not further impacted following ET. In conclusion, the

ET period has a detrimental impact on biomechanical and physiological measures and increases creatine kinase activity in the days following 120-min of soccer-specific exercise. The impact of ET on recovery and subsequent performance should be investigated following 90- and 120-min of actual match-play.

ACKNOWLEDGEMENTS

I could never have imagined that six years ago, as I walked through the doors at the University of Huddersfield, that I would be leaving with a PhD. The way in which I have developed as both an academic and as a person is testament to the support network around me. I can say wholeheartedly that I have enjoyed every moment of the experience and I wish to reach out to those who have supported my efforts along what has been an incredible journey.

Steve Lui, thanks for being my 'lay' reader and for your valuable contribution to the systematic review. Matt Haines, you are an amazing academic, person and you have inspired me since my first year to better myself. I have learned so much from you and hope that I continue to work with you throughout the rest of my career. Thanks for all the support and I am truly honoured to have worked with you; I hope one day I can engage an audience the way you can. Rick Page, I will never be able to thank you enough for the dedication, devotion and time dedicated towards supporting my development. Despite often doubting myself, you have always believed in me and given me confidence to believe in my academic ability. You have been so much more than just a supervisor and we have developed a strong friendship and I truly hope we remain lifelong friends. Liam Harper, the best decision I made was choosing you as my main supervisor. You have challenged me to grow as an academic and gave me support and space in perfect harmony – for that I am grateful. You have a vision for the future and your carefully considered guidance places me in a great position post PhD. Put simply, you are the person I aspire to be, and I hope we continue to collaborate in the future and remain friends for many years to come. Liam Corr, I have been fortunate to have you by my side throughout this experience. You have been an ear, allowed me to pick your brains and been a great friend throughout. I hope one day we can work together again, and this is a friendship that will last a lifetime — my good pal 'Dr Chocolate'.

To my friends Dawson and Porter, and extended family Brenda, grandad David, Peter, George, Rita, Chloe, Steve and Cathi, thanks all for helping me in your own ways throughout my time at university. My cousins – Leah, George and Madison, thanks for being there for me and I love you all dearly. To my girlfriend Lauren, you are the one who persuaded me to apply for university all those years ago. You have been there every step of the journey supporting and loving me and I will be eternally grateful to you for helping me become a better person – I love you and I hope to spend the rest of my life with you. To my wonderful nan Christine, I will never be able to repay you for all you have ever done for me and your constant support throughout my life has helped me become the person I am. My dad Dave, for being the person that has always encouraged me to follow my dreams and reach for the stars. I love you and without your guidance and wisdom I would not be half the person I am today. My mum Lisa, you are the person I would trust with my life and I owe you the biggest thank you for the unconditional love and continual support – I love you more than you could ever imagine. To my late grandad fish – since as long as I can remember you have encouraged that I go to university and shown a keen interest in my life. I dedicate this thesis to you.

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Copyright statement

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TABLE OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Full-term
Acc	Acceleration
AIC	Akaike's Information Criterion
AR-1	First Order Auto-Regressive
AST	Aspartate Aminotransferase
AU	Arbitrary Units
$BEAST_{90}$	The Ball-Sport Endurance and Sprint Test
BLa	Blood Lactate
CHERRIES	Checklist for Reporting Results of Internet e-Surveys
CHO	Carbohydrate
CI	95% Confidence Interval
CK	Creatine Kinase
CMJ	Countermovement Jump
CO_2	Carbon Dioxide
CoD	Change of Direction
conKE	Concentric Knee Extensors
CT	Contraction Time
CV	Coefficient of Variation
CST	Copenhagen Skills Test
Dec	Deceleration
d-RPE	Differential Ratings of Perceived Exertion
eccKF	Eccentric Knee Flexors
EMG	Electromyography
EMG_{BF}	Electromyography activity of the biceps femoris
EMG_{RF}	Electromyography activity of the rectus femoris
E (n)	Epoch (Number)
ES	Effect Size
ET	Extra-Time
FIFA	Fédération Internationale de Football Association
FWC	FIFA World Cup
GDPR	General Data Protection Regulation
GI	Glycaemic Index
GPS	Global Positioning System
HR	Heart Rate
HR_{max}	Maximum Heart Rate
HR_{mean}	Mean Heart Rate

HS	High Speed
HT	Half-Time
H:Q ratio	Hamstrings-to-Quadriceps Ratio
ICC	Intra-Class Correlation Coefficient
IFAB	International Football Association Board
IL-6	Interleukin-6
iSPT	Intermittent Soccer Performance Test
LIST	Loughborough Intermittent Shuttle Test
LMM	Linear Mixed Model
MEMS	Micromechanical electrical systems
MEP	Motor Evoked Potential
Mmax	Maximal M-wave
MRFD	Maximum Rate of Force Development
MRR	Maximum Rate of Relaxation
N_2	Nitrogen
NEFA	Non-Esterified Fatty Acids
O_2	Oxygen
PL	PlayerLoad™
PLA	Placebo
$PL_{A\text{-}P}$	Anterior-Posterior PlayerLoad™
$PL_{A\text{-}P\%}$	Relative Contribution of Anterior-Posterior PlayerLoad™
$PL_{M\text{-}L}$	Medial-Lateral PlayerLoad™
$PL_{M\text{-}L\%}$	Relative Contribution of Medial-Lateral PlayerLoad™
PL_{Total}	Tri-Axial PlayerLoad™
PL_V	Vertical PlayerLoad™
$PL_{V\%}$	Relative Contribution of Vertical PlayerLoad™
PPT	Pain Pressure Threshold
PPT_{BF}	Pain Pressure Threshold for Biceps Femoris
PPT_{RF}	Pain Pressure Threshold for Rectus Femoris
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-analyses
r	Pearson’s Correlation Coefficient
RER	Respiratory Exchange Ratio
RF	Rectus Femoris
RMS	Root Mean Square
RPE	Rating of Perceived Exertion
RPE-B	Central/Breathlessness Ratings of Perceived Exertion

RPE-L	Local/Peripheral Ratings of Perceived Exertion
RPE-O	Overall Ratings of Perceived Exertion
RSA	Repeated Sprint Ability
RSI	Reactive Strength Index
RT0.5	Half Relaxation Time
$SAFT_{90}$	Soccer Aerobic Fitness Test
SD	Standard Deviation
SE	Standard Error
SEM	Standard Error of Measurement
SMS	Soccer Match Simulation
SSC	Stretch Shortening Cycle
SSIET	Soccer-Specific Intermittent-Exercise Test
TD	Total Distance
TE	Typical Error
UEFA	Union of European Football Associations
VAS	Visual Analogue Scale
VL	Vastus Lateralis
$\dot{V}O_2$	Volume of Oxygen Consumption
$\dot{V}CO_2$	Volume of Carbon Dioxide Consumption
$\dot{V}O_{2max}$	Maximal Oxygen Consumption
$\dot{V}O_{2mean}$	Mean Oxygen Consumption
$\dot{V}O_{2peak}$	Peak Oxygen Consumption
YYIET	Yo-Yo Intermittent Endurance Test

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1.0 GENERAL INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Association football (otherwise known as and herein referred to as soccer) is a team sport that comprises an intermittent activity profile with frequent sprint actions, high-speed efforts, accelerations, decelerations and change of direction (CoD) elements interspersed by low-intensity and stationary periods of activity. Over recent years, soccer has grown in worldwide popularity. As such, the concomitant increases in broadcasting revenues, merchandise and ticket sales have driven the need for novel research, ultimately for the purpose of successful team performance and player health. The evolving demands of soccer has also seen contemporary investments in staff that fulfil roles as sports scientists and strength and conditioning coaches to address the gap between science and practice (Nosek et al., 2021; Read et al., 2018). As such, evolving research questions and apposite research designs are required for the purpose of applying research-based evidence to the current approaches and practices employed within soccer (Harper et al., 2016d; Hills et al., 2020; Weston, 2018). However, although a wealth of robust soccer studies are available in relation to 90 min of simulated soccer-specific exercise (Page et al., 2015; Russell et al., 2011a; Small et al., 2010) and actual match-play observations (Barrett et al., 2016; Bradley et al., 2009; Carling & Dupont, 2011), considerably less research attention has been given to the additional 30 min period termed extra-time (ET).

Soccer matches are traditionally competed over 90-min, comprising two 45-min halves, interspersed with a 15-min half-time (HT) break. However, when scores remain level after 90-min in the knockout phase of some major international tournaments and domestic cup competitions, matches proceed to ET (Harper et al., 2016d). This additional period is 30 min in duration, commencing 5 min after the end of the normal 90 min period and contested as two 15 min halves, separated by a two min break (Harper et al., 2016a). If matches remain tied at the end of ET; the winning team is determined by a penalty shootout (Jordet & Elferink-Gemser, 2012; Lenten et al., 2013). The prevalence of ET is pronouncedly less common with comparison to typical 90 min matches, although over recent years has become increasingly common in tournament knockout phase match-play. For instance, 36% of the previous four Fédération Internationale de Football Association (FIFA) World Cup knockout phase matches have proceeded to ET, including 38% of matches at the 2006 FIFA World Cup, 25% at the 2010 tournament, 50% of matches at the 2014 competition and 31% of matches at the 2018 FIFA World Cup (www.FIFA.com).

Despite the occurrence of matches that require ET in cup competitions and tournaments, there remains a disproportionate quantity of scientific literature that has documented aspects of this additional period versus traditional 90-min matches. This is surprising given the importance of this additional period of match-play in determining success in major tournaments (Goodall et al., 2017). Matches that require ET also hold great economic and societal importance, with professional soccer practitioners attributing a high degree of importance to this additional 30 min period, especially in determining the outcome of cup competitions and tournament success (Harper et al., 2016d). Furthermore, matches that are resolved during this timeframe do not proceed to penalties, with critics claiming that the outcome of a shootout is a lottery as opposed to a true separation of quality (Lenten et al., 2013). As such, gaining a broader perspective of a wide range of under researched aspects specific to ET will ultimately provide teams with an advantage during and following this fundamental period of additional play.

The paucity of research concerning 120 min of soccer implies that there is a lack of understanding as to whether ET has a detrimental impact on fatigue, performance and recovery compared with a typical 90 min match. Therefore, it is unclear what specific practices should be adapted in relation to the ET period. For this reason, it seems likely that practitioners and coaches use the same approaches to performance and recovery that have been validated for 90 min of soccer, with little evidence as to the efficacy of such practice with reference to ET matches. There is also little feedback from within the applied setting seeking practitioner views on the approach that research should take moving forward. Such information may enable the implementation of study designs that overcome the many complexities involved with operating in the field. Such lack of knowledge may have negative implications for practice given that contemporary soccer schedules are associated with fixture congestion that can lead to an insufficient time to recover between matches (Carling et al., 2015; Carling et al., 2012; Dellal et al., 2015), with games that proceed to ET often competed amid such fixture dense schedules (Julian et al., 2020a; Winder et al., 2018).

Given the limited research presently available in relation to ET, this chapter will appraise previous work that has assessed 90 min of soccer for the purpose of implying potential approaches to addressing gaps in the ET evidence-base. The aim of this chapter is to: (1) synthesise information related to the use of soccer-specific protocols and the factors that may guide researchers in relation to selecting an ideal protocol for the research outcome, (2) evaluate the use of biomechanical and physiological measures within soccer-specific exercise protocols to elucidate research gaps, (3) appraise the use of recovery markers within a soccer-specific context with a view to justifying their use and identifying areas that require exploration within the literature, and (4) identify the impact and time course of recovery following soccer-specific activity. In addition to appraising relevant literature and highlighting gaps in research, this chapter will also provide a rationale for the methodological approaches taken throughout this thesis.

1.2 SIMULATING SOCCER MATCH-PLAY

Soccer match-play offers supreme ecological validity, although there are practical restrictions on how data can be collected (Drust et al., 2000b), and matches are susceptible to contextual factors such as pacing strategies, match location, opponent level and match result, which perhaps influence player performance, particularly from an effort perspective (Abbott et al., 2018b; Barrett et al., 2018; Castellano et al., 2011). Between-match physical performance metrics are highly variable (Carling et al., 2016) which makes it inherently difficult to manipulate variables to establish cause and effect. As such, soccer-specific exercise simulations have been validated to mimic the internal (e.g., heart rate [HR], blood lactate [BLa] and rating of perceived exertion [RPE]) and external demands of soccer (e.g., distance covered, number of sprints, accelerations and decelerations) whilst controlling the influence of confounding variables external to the study outcome measures (Brito et al., 2016; Silva et al., 2018).

Soccer-specific simulations can be broadly partitioned into two specific categories; free-running protocols and laboratory-based treadmill protocols (Silva et al., 2018). The consideration given to which type of simulation to use needs to be considered in relation to the research question. For example, a study investigating CoD may choose to utilise a free-running protocol (Russell et al., 2011b). Whereas, a study interested in performance using an environmental chamber, may necessitate an indoor treadmill-based protocol (Taylor et al., 2014). Ultimately, the most important consideration in relation to the choice of protocol is that they should be considered on a spectrum with match-play at one end, thus high ecological validity, and treadmill-based simulations at the other end offering the highest experimental control. With the above in mind, this section will identify and appraise previous free-running and treadmill-based soccer-specific protocols.

1.2.1 Free-running soccer-specific protocols

Free-running soccer-specific protocols, otherwise referred to as over-ground running simulations or field-based protocols offer an appealing mode of replicating match demands whilst providing an increased ecological validity compared with controlled laboratory-based settings. There have been several free-running simulation models developed to provide a stimulus that closely replicates the demands associated with soccer match-play (Table 1.1).

Table 1.1. An overview of the studies using novel free-running soccer-specific exercise protocols

Reference	Protocol Duration	Protocol Distance	Activity profile	Additional Details
Bishop et al. (1999)	2 x 45 min halves with 15 min passive half-time period	9.7 km	6 x14 min bouts of 7 x 2 min circuits which comprised 50 m walk, 50 m backwards run, 25 m cruise run, 25 m sprint and 50 m dribbles	Intermittent exercise protocol incorporating ball dribbling
Nicholas et al. (2000)	5 x 15 min bouts with 3 min passive recovery followed by a run (~10 min) to volitional exhaustion	12.4 km	Part A: Repeated 3 x 20 m walks, 1 x 20 m sprint, 4s rest, 3 x 20 m at 55% $\dot{V}O2_{max}$, and 3 x 20 m at 95% $\dot{V}O2_{max}$ Part B: Alternate 20m shuttles at 55 and 95% $\dot{V}O2_{max}$ until volitional exhaustion	'Loughborough Intermittent Shuttle Test' (LIST)
Currell et al. (2009)	2 x 45 min halves with 15 min passive half-time period	Total distance undisclosed	10 x 6 min with 4 x repeated 90 s blocks which comprised walking (10 s), jogging (10 s; 50% PSS), cruising (10 s; 95% PSS), jogging (10 s), cruising (10 s), walking (15 s), sprinting (5 s), jogging (15 s), and sprinting (5 s)	Based on Ekblom (1986) field test incorporating kicking, dribbling and heading tests
Small et al. (2009b)	2 x 45 min halves with 15 min passive half-time period	10.8 km	Repeated 15 min bouts of 20 m shuttle activity with speeds and activity directed by audio cues. Navigate the initial pole (2 m from start) with either backwards or lateral movement, run forwards through the course whilst side stepping the 3 middle poles	'Soccer-Specific Aerobic Field' Test ($SAFT^{90}$)
Williams et al. (2010)	2 x 45 min halves with 15 min passive half-time period	8.1 km	Repeated completion of 2 x laps of a 380 m circuit comprising sprints (8.4%), backward jog (8.4%), walk (9.7%), jog/decelerations (24.5%), run at ~75% of maximum effort (39%), jumping and shooting tasks	'Ball Sport Endurance and Sprint Test' ($BEAST_{90}$) incorporating vertical jumps and shooting tasks

Russell et al. (2011a)	2 x 45 min halves with 15 min passive half-time period	10.1 km	7 x 4.5 min periods of activity with 3 x repeated cycles of 3 x 20 m walking, alternate 20 m dribbling test or 15 m sprinting, a 4s rest, 5 x 20 m jogs at 40% $\dot{V}O2_{max}$, 1 x 20 m backwards jog at 40% $\dot{V}O2_{max}$, and 2 x high-speed runs completed at 85% of predicted $\dot{V}O2_{max}$. Following each bout, a 1 min passing test and 1 min passive rest was completed	'Soccer Match Simulation' incorprating dribbling, passing and shooting tasks
Bendiksen et al. (2012)	2 x 45 min halves with 15 min passive half-time period	11.3 km	18 x 5 min periods of activity comprised of walking (152 m; ~6 $km \cdot h^{-1}$), jogging (171 m; ~8 $km \cdot h^{-1}$), low (69 m; ~12 $km \cdot h^{-1}$), moderate (41m; ~15 $km \cdot h^{-1}$), high-speed running (55m; ~18 $km \cdot h^{-1}$); sprinting (2 x 20m; ~6 $km \cdot h^{-1}$), backwards running (30 m; ~8 $km \cdot h^{-1}$), and backwards or sideways running (20 m; ~8 $km \cdot h^{-1}$).	'Copenhagen Soccer Performance Test' incorporating dribbling, passing and shooting tasks
Kunz et al. (2019)	2 x 40 min halves with 10 min passive half-time period	8.1 km	Repeated 30 rounds (160 s each) of jogging (120 m; 45%), sprinting (20 m; 7%), walking (90 m; 33%), 1 x countermovement jump and an agility test in response to visual stimuli (40 m; 15%)	Sprinting, jumping and agility tasks incorporated

The first published work to have developed a free-running soccer simulation were that of Bishop et al. (1999). Although the protocol was based on notational data (Bangsbo et al., 1991), and evoked a BLa response (4—5 mmol·l^{-1}) consistent with match-play (Bangsbo et al., 2007), the distances covered were invalid for each of the locomotor categories and there were a disproportionate quantity of speed changes incorporated (Di Salvo et al., 2007; Mohr et al., 2003; Rampinini et al., 2007). Other commonly utilised free-running protocols are that of the Loughborough Intermittent Shuttle Test (LIST) (Nicholas et al., 1995) and Soccer Aerobic Fitness Test (SAFT^{90}) protocols (Small et al., 2009a). Both protocols are similar in that players perform 20 m shuttle runs with audio signals regulating the speeds and activity profile. Despite both being designed to replicate match-play, the LIST overemphasises high-speed activity (Barnes et al., 2014; Di Salvo et al., 2007; Rey et al., 2010) and the SAFT^{90} (Small et al., 2009a) incorporates almost double the number of CoD (*n* = 1350 versus match-play *n* = 726), and to a greater magnitude (i.e. 180 degrees), than those commonly reported during match-play (Bloomfield et al., 2007). As such, it can be inferred that although these protocols are reflective of the distances covered across 90 min, the validity of the activity profile may not be a valid representation of competitive match-play.

The Ball-Sport Endurance and Sprint Test (BEAST$_{90}$) (Williams et al., 2010) and the Soccer Match Simulation (SMS) (Russell et al., 2011b) are 90-min protocols. Both protocols incorporate technical elements into their design, but have prolonged periods of stationary activity. Despite the BEAST$_{90}$ demonstrating good reliability, the total distance covered (8.1 km) falls short of the values reported during professional match-play (Barnes et al., 2014; Mohr et al., 2003). The SMS was adapted from the LIST (Nicholas et al., 2000), with the physiologcial responses (BLa and HR), as well as the distances covered, passess, shots and dribbles largely reflecting the numbers reported in compeititve soccer matches (Ali & Farrally, 1991; Bangsbo et al., 2007; Bloomfield et al., 2007). However, the low number of speed changes are not analogous with match profiles (Di Salvo et al., 2007; Mohr et al., 2003). The duration of the SMS has since been adapted (i.e., incorporating an ET period) and demonstrated good reliability across 120 min (Harper et al., 2016d).

The Copenhagen Skills Test (CST) (Bendiksen et al., 2012) reflects the total distance, high-speed and sprinting distances performed during match-play (Mohr et al., 2003). The protocol was designed to implement match activity profiles in relation to the amount of time spent with the ball, number of headers, shots and passes, as well as soccer-specific movements and changes in speed (Barnes et al., 2014; Bloomfield et al., 2007). Within-simulation measures of HR and muscle glycogen were also comparable with match-play data (Bangsbo et al., 2006; Mohr et al., 2012). However, although the protocol accurately reflects the demands and physiological responses elicited during match-play, the test was limited in feasibility due to the complex nature of the design and the space needed to carry out the protocol. Creatine kinase (CK) markers were taken as indirect markers of muscle damage recovery up to 24 hr post protocol with values being consistent with those at the corresponding time point following a competitive match in the same population of players. Kunz et al. (2019) developed an 80-min soccer-specific free-running protocol in youth players, with a total of 8.1 km performed, which is lower than reported in the notational analysis literature in senior professional players (Barros et al., 2007; Bradley et al., 2009; Mohr et al., 2003). Within-trial measures were taken including oxygen uptake, respiratory exchange ratio (RER), HR, BLa, and differential ratings of perceived exertion (d-RPE). The d-RPE increased as a function of time, and BLa (Krustrup et al., 2006) and HR values (Mendez-Villanueva et al., 2013; Rebelo et al., 2014) were representative of responses associated with match-play. Furthermore, recovery assessments were conducted using measures of CK, perceived muscle soreness using a visual analogue scale (VAS), CMJ height and knee flexor and extensor strength. It was revealed that the CK and VAS remained elevated up to 24 hr, though returned to pre-values by 48 hr. However, the protocol utilised youth players, which have previously elicited divergent physiological responses compared with adult players (Dellal et al., 2011b; Wong et al., 2010), thus the status of the participants limits evaluation of the responses.

1.2.2 Laboratory-based treadmill protocols

Laboratory-based treadmill designs remain limited such that isolated skill actions are incapable of being implemented, the physiological fatigue response observed during match-play in not always accurately replicated and indeed, are inherently unidirectional (Bendiksen et al., 2012; Greig & Siegler, 2009; Russell & Kingsley, 2011). However, treadmill-based protocols require limited space, offer high experimental control, and closely represent the mechanistic profile of match-play compared with free-running protocols (Harper et al., 2016d; Page et al., 2015, 2019; Silva et al., 2018). Treadmill simulations can be sub-divided into two classifications, that is, non-motorised and motorised. Non-motorised treadmills are characterised by a freely moveable treadmill belt that is powered by the individual, whereas, motorised treadmills are powered by a motor and remain constant until actively modified (Montgomery et al., 2016). Both designs have merit in that non-motorised treadmills enable instantaneous speed changes and near maximal speeds to be attained (Sirotic & Coutts, 2008; Tofari et al., 2015), while, motorised treadmills are preferred in the sense that distances and intensities can be standardised so that any changes observed in a given measure are likely to be fatigue-induced (Page et al., 2015). As reported in Table 1.2, both designs of treadmill-based soccer-specific exercise protocols have been developed to assess various aspects of soccer.

1.2.2.1 Non-motorised treadmill-based protocols

The soccer-specific intermittent-exercise test (SSIET) is a non-motorised soccer-specific treadmill-based protocol (Oliver et al., 2007) designed to replicate the activity profile performed during one half of competitive match-play (Bangsbo et al., 1991; Mohr et al., 2003). Although the BLa and HR responses elicited by the protocol were consistent with previous match-play data (Bangsbo et al., 2007; Thatcher & Batterham, 2004), players sprinted a total of 551 ± 36 m, which is greater than that observed in time-motion analysis data (Bangsbo et al., 1991; Mohr et al., 2003). Sirotic and Coutts (2008) developed the team sport simulation to mimic the activity profile of several intermittent team sports, including soccer (Appleby & Dawson, 2002; Bangsbo et al., 1991; Duthie et al., 2003; Meir et al., 1993). The activity profile was taken from time-motion analyses soccer observations (Bangsbo et al., 1991), however, the total, high-speed and sprint distances covered, as well as the activity changes completed, underestimated those previously observed in team sports and soccer (Mohr et al., 2003; Spencer et al., 2004). Therefore, although the above simulations have merit, the invalid activity profile fails to represent soccer match-play.

The Intermittent Soccer Performance Test (iSPT) was developed as a non-motorised treadmill soccer-specific protocol (Aldous et al., 2014). The simulation was developed alongside time-motion analyses soccer match-play data (Abt, 2002); however, total and high-speed distances covered as well as the disparity in sprint durations (i.e., ~3.5 s shorter during match-play) limit its validity in comparison with professional soccer matches (Barnes et al., 2014; Bloomfield et al., 2007; Mohr et al., 2003). Furthermore, the university-standard players used fails to represent the population for which the protocol was based (Abt, 2002). Therefore, although the physiological response elicited was similar to match-play (Akubat et al., 2014), the evaluation of the specific pool of participants makes accurate interpretations difficult.

Table 1.2. An overview of the studies using novel non-motorised and motorised treadmill-based soccer-specific exercise protocols

Reference	Protocol	Protocol Duration	Protocol Distance	Activity profile	Additional Details
Abt et al. (1998)	Motorised treadmill	60 min	11.2 km	9 x cycles which comprised 5 min medium-speed running (individualised), 30 s high-speed running (individualised) and 75 s low-speed (4 $km \cdot h^{-1}$). High and medium speeds corresponded to 100 and 75 % of an individual's $\dot{V}O2_{max}$	Dribbling and shooting tasks were performed pre- and post-simulation
Drust et al. (2000b)	Motorised treadmill	2 x 45 min halves with 15 min passive half-time period	Total distance undisclosed	4 x 22.5-min cycles which comprised 6 x walking (35.3 s; 6 $km \cdot h^{-1}$), 6 x jogging (50.3 s; 12 $km \cdot h^{-1}$), 3 x cruising (51.4 s; 15 $km \cdot h^{-1}$) and 8 x sprinting (10.5 s; 21 $km \cdot h^{-1}$)	'Drust protocol' 0% treadmill gradient
(Drust et al., 2000a)	Non-motorised	2 x 45 min halves with 15 min passive half-time period	9.5 km	3 x 5 min cycles with 11 repeated activities which comprised 3 x standing (0 $km \cdot h^{-1}$), 3 x walking (4 $km \cdot h^{-1}$), 3 x jogging (8 $km \cdot h^{-1}$), 1 x cruising (12 $km \cdot h^{-1}$) and 1 x sprinting (maximal).	No specific description of pacing was present
Thatcher and Batterham (2003)	Non-motorised treadmill	2 x 45 min halves with 15 min passive half-time period	Total distance undisclosed	9 x 5 min repeated cycles which comprised 3 x standing (3.64s x 4; 0 $km \cdot h^{-1}$), 8 x walking (4.3 s x 4; 5 $km \cdot h^{-1}$), 7 x jogging (3.58 s x 4; 10 $km \cdot h^{-1}$), 2 x running (3.82 s x 3; 17 $km \cdot h^{-1}$) and 1 x sprinting (2.8s; 23 $km \cdot h^{-1}$)	2% treadmill gradient
Greig et al. (2006)	Motorised treadmill	2 x 45 min halves with 15 min passive half-time period	9.7 km	6 x 15 min which comprised 20 x standing (7.8 s; 0 $km \cdot h^{-1}$), 55 x walking (6.7 s; 4 $km \cdot h^{-1}$), 42 x jogging (3.5 s; 8 $km \cdot h^{-1}$), 46 x low-speed running (3.5 s; 12 $km \cdot h^{-1}$), 20 x moderate-speed running (2.5 s; 16 $km \cdot h^{-1}$), 9 x high-speed running (2.1 s; 21 $km \cdot h^{-1}$) and 3 x sprinting (2.0 s; 25 $km \cdot h^{-1}$)	2% treadmill gradient

Oliver et al. (2007)	Non-motorised treadmill	48 min	4.8 km	7 x 2 min periods which comprised 45 s walking (4 km·h^{-1}), 15 s cruising (12 km·h^{-1}), 15 s stationary, 40 s jogging (8 km·h^{-1}) and a 5 s maximal sprint	‘Soccer-specific Intermittent-exercise Test’ (SSIET)
Sirotic and Coutts (2008)	Non-motorised treadmill	30 min	3.4 km	2 x 15 min periods with 2 min rest. Each 15 min bout comprised standing (0% PSS), walking (20% PSS), jogging (35% PSS), running (45% PSS), fast running (65% PSS) and sprinting (100% PSS)	Maximal sprint speed test followed by 30 min intermittent exercise
Aldous et al. (2014)	Non-motorised treadmill	2 x 45 min halves with 15 min passive half-time period	8.9 km	3 x 15 min comprised of standing (0% PSS), walking (20% PSS), jogging (35% PSS), running (50% PSS), fast running (60% PSS), variable run (unset), sprinting (100% PSS)	‘Intermittent Soccer Performance Test’ (iSPT)
Page et al. (2015)	Motorised treadmill	2 x 45 min halves with 15 min passive half-time period	12.2 km	6 x 15 min which comprised 29 x standing (7.0 s; 0 km·h^{-1}), 65 x walking (6.4 s; 4 km·h^{-1}), 53 x jogging (3.0 s; 8 km·h^{-1}), 48 x low-speed running (2.6 s; 11.6 km·h^{-1}), 17 x moderate-speed running (2.2 s; 15 km·h^{-1}), 12 x high-speed running (2.1 s; 18 km·h^{-1}) and 7 x sprinting (2.5 s; 25 km·h^{-1})	1—2.5% treadmill gradient

1.2.2.2 Motorised treadmill-based protocols

The earliest motorised treadmill-based soccer protocol was developed by Drust et al. (2000b) based on the locomotion profile (Reilly, 1976) and duration spent at each of the velocity profiles during match-play (Van Gool et al., 1988). The protocol incorporates 46 speed changes equating to 92 per 90 min match, which is substantially less than the average (i.e., 1000—1500) observed during match-play (Barnes et al., 2014; Bloomfield et al., 2007; Di Salvo et al., 2007; Mohr et al., 2003). The duration of each velocity distribution category was in excess of those observed during professional soccer matches (Bangsbo et al., 1991; Barros et al., 2007; Mohr et al., 2003). Despite evoking HR values that are similar to those observed previously during match-play (Van Gool et al., 1988), the protocol failed to accurately reflect the profile of soccer match-play and is unable to be considered valid.

A treadmill-based soccer-specific exercise protocol (Greig et al., 2006) intended to mimic the intermittent nature of soccer, based the activity profile on notational data (Bangsbo, 1994a). Despite the high number of speed changes completed within the protocol, the simulation did not elicit a physiological response consistent with match-play (Bangsbo, 1994a; Bangsbo et al., 2007; Ispirlidis et al., 2008). Participants completed 18 sprints at 25 $km \cdot h^{-1}$ for a mean duration of two seconds which equates to a far lower sprint distance covered when considered against match-play (Barros et al., 2007; Bloomfield et al., 2007; Mohr et al., 2003). As such, the treadmill-based simulation may be constrained in its ability to reflect the sprint activity of professional soccer.

A contemporary motorised treadmill-based soccer simulation was developed by Page et al. (2015) based on the durations, velocities and locomotion profile of previous notational analyses (Mohr et al., 2003). The protocol was designed to simulate the high-speed clusters interepsersed with lower speed bouts identified previously during matches (Spencer et al., 2004). The acceleration settings were set at the treadmill limit (1.39 $m \cdot s^{-2}$) to better replicate over ground speed changes. Changes to the treadmill elevation were also applied to account for the reduced drag associated with testing indoors (Jones & Doust, 1996). However, although this alteration may be required for replicating the aerodynamics of outside running, the mechanics associated with running at differing gradients may not be fully elucidated. Total distance covered was 12.2 km (Bradley et al., 2009; Di Salvo et al., 2007; Mohr et al., 2003), the number of speed changes completed was ~1386, and the 8:1 ratio of high- and low-speed activity were synonymous with match-play (Reilly, 1997). The HR values (162—172 $b \cdot min^{-1}$) observed were also similar to those reported during match observations (Mohr et al., 2003; Mohr et al., 2012). Likewise, the BLa concentrations evoked during the protocol (3.2 ± 2.1 $mmol \cdot l^{-1}$) are near the lower end of the range (2—10 $mmol \cdot l^{-1}$) previously reported during match-play (Bangsbo et al., 2007). The biomechanical response as evidenced by the

PlayerLoad™ patterns were largely reflective of data collected from 63 English championship players across 86 competitive soccer matches (Barrett et al., 2016). Therefore, it appears that the above protocol accurately reflects match observations in replicating the activity profile and elicits physiological and biomechanical responses synonymous with match-play. The same research group have since used the protocol to assess the influence of a simulated fixture congested period on residual recovery and subsequent fatigue measures (Page et al., 2016; Page et al., 2019). However, to date, the reliability of the protocol has yet to be assessed, and thus, such an investigation appears warranted.

1.2.3 Summary

Despite competitive soccer matches offering the ideal mode for researchers intending to capture an ecological picture of match demands, this form of data collection yields logistical difficulty, especially for within-match biomechanical and physiological fatigue assessments. Therefore, researchers have developed soccer match simulations as a feasible alternative to replicate the demands of the game, enabling biomechanical and physiological aspects of soccer performance to be evaluated. For ultimate validity, the development of a protocol must be considered in relation to replicating the intermittent activity patterns of soccer, whilst attempting to elicit a response to the exercise stress that is synonymous with match-play (Drust et al., 2007). Some studies have validated protocols by having the same group of participants complete both experimental conditions, including the simulation and an actual match, and subsequently comparing the responses (Bendiksen et al., 2012). Although this may be considered an ideal approach to protocol validation, soccer-specific exercise simulations are often designed based on average data collected across an entire team or a cohort of players (Russell & Kingsley, 2011), with individual variance rarely considered or reported. It is also important that the disparities in individual responses and activity profiles of discrete playing positions are taken into account (Bush et al., 2015; Di Salvo et al., 2007). Owing to the constantly evolving nature of match-play and the increasing physical performance demands (Barnes et al., 2014; Bush et al., 2015); new soccer simulations should be developed and validated against contemporary match demands. It is integral that the simulation is developed in relation to a rigourous (e.g., laboratory-based) or an ecologically valid (e.g., free running simulation) agenda.

As alluded to throughout section 1.2, the use of free-running simulations tends to offer additional ecological validity when compared to treadmill-based simulations in that they allow the incorporation of CoD, backwards and lateral movements, and skill elements such as ball dribbling. Including these actions has also shown to increase the energy output versus with the absence of a ball (Reilly, 1997) and exercise is strictly uni-directional (i.e., treadmill-simulations) (Stevens et al., 2015). However, the exercise intensity may suffer as a consequence, particularly if the ability of the players comprises skill acquisition and their capabilities of maintaining ball control (Russell & Kingsley, 2011). Furthermore, free-running simulation protocols possess lower reliability due to the reduced experimental control and increased variability of the activity profile (i.e., ability to pace activity during the latter stages when fatigued) (Tofari et al., 2015). Logistical considerations may also impact the selection of protocols. Free-running protocols necessitate a vast area, potentially limiting its practical compatibility for researchers with restricted access to a large facility. However, numerous participants can simultaneously undertake a free-running soccer-specific exercise protocol, thus, researchers with a time efficient agenda may benefit from the reduced time burden involved with testing. On the other hand, the treadmill itself can be expensive versus the cost-effectiveness of free-running protocols and testing is often limited to treadmill accessibility.

Laboratory-based treadmill protocols have been advocated as they provide researchers with ultimate experimental control that is needed to reliably assess the fatigue responses during soccer-specific exercise (Page et al., 2016). In addition, distances and intensities can be standardised so that any changes observed in each measure are likely to be fatigue induced (Page et al., 2015). However, non-motorised treadmills fail to eliminate the pacing element associated with match-play and free running simulations, and as such, motorised treadmills are favoured when protocols are intended to systematically elicit total control over distances and intensities covered. Previously, the potential differences in gait characteristics associated with treadmill and free running, and the implications this may have when comparing the physical response have been considered (Page et al., 2015). However, contemporary research suggests that treadmill-based running is largely comparable with free running in relation to kinematic, kinetic, mechanical, musculotendinous and spatiotemporal outcomes (Van Hooren et al., 2019). Furthermore, it is key that researchers interested in assessing recovery following soccer must consider the mode of soccer-specific exercise against the characteristics required for control and standardisation of the recovery response.

Soccer match-play is inherently ‘unpredictable’ in nature which can result in high inter-individual variability in aspects such as the recovery response elicited (Nédélec et al., 2012). Therefore, should researchers wish to investigate the biomechanical, physiological and recovery responses during or following a soccer stimulus, using motorised treadmill protocols seems most appropriate due to the increased experimental control that can be established over the activity profile limiting external influences and evoking reliable responses to exercise (Russell & Kingsley, 2011). As mentioned above, researchers have extended the duration of free-running protocols to 120 min to assess changes in response to the ET period. However, to date, there has been no such adaption to laboratory-based treadmill protocols (shown to possess maximum experimental control over the activity profile and limit confounding factors) which appear ideal for investigating biomechanical and physiological fatigue, and the recovery response. As such, there may be scope to investigate the impact that 120-min of controlled treadmill-based simulated soccer match-play has on aspects of biomechanical and physiological fatigue, and recovery.

1.3 BIOMECHANICAL RESPONSES TO SOCCER-SPECIFIC EXERCISE

The differing methods used in sport and exercise that constitute being labelled a 'biomechanical measure' are not well established. Indeed, the study of biomechanics covers a wide range of measurable quantities in human motion analyses from the external forces applied to tissues and structures to the movement and function of the neuromuscular system (Lu & Chang, 2012). Soccer-specific biomechanical indices are often used to assess kicking and throwing actions (Dørge et al., 2002; Kellis & Katis, 2007), injury risk and prevention (Cabello et al., 2015; Thompson et al., 2017), the etiology of fatigue (Brownstein et al., 2017; Thomas et al., 2017), and changes in physical performance and running mechanics (Page et al., 2015; Page et al., 2016; Page et al., 2019). Although match-play provides high ecological validity for assessing the physical responses, there are practical constraints involved with using many biomechanical techniques during match scenarios (Verheul et al., 2020). Therefore, as match-play is not congruent with taking biomechanical measures; simulating the demands of matches provides a feasible alternative. However, free-running and non-motorised treadmill designs are limited in that they fail to standardise player running activity (Aldous et al., 2014; Harper et al., 2016d); therefore, motorised treadmill-based variants are preferable to enable researchers to interpret the biomechanical differences between equal and fixed bouts of activity (Page et al., 2019).

1.*3.1 Surface electromyography*

Surface electromyography (EMG) is the procedure of monitoring the electrical activity produced by muscles derived from the placement of electrodes on the skin surface (Phinyomark et al., 2020). Muscle activation refers to the magnitude of neural drive to a specific muscle with reference to motor unit recruitment and modulation rate (Besomi et al., 2020). Changes in muscle activation are reflected by an altered EMG activity, which can be used to identify motor unit activation patterns for inferring that fatigue occurs centrally along the motor pathway in response to exercise (Hill et al., 2016). Fatigue at the central level (central fatigue) can manifest as an inhibited central nervous system capacity to activate skeletal muscle that results in force decrements (Thomas et al., 2017). However, the level at which fatigue is present along the motor pathway is unclear and the precise origin (central or peripheral) is difficult to measure directly due to the complex relationship of the physiological and psychological processes. Therefore, indirect measures (i.e., EMG) are often taken to draw inferences of the fatigue source. Additionally, evaluating muscle activity and collecting such data during competition is impractical given the difficulties involved with affixing electrodes and maintaining their precise anatomical position on the limb. Therefore, instead of collecting data during actual competitive match-play, EMG assessments are typically conducted during simulated soccer-specific exercise (Brownstein et al., 2017; Goodall et al., 2017; Greig et al., 2006; Marshall et al., 2014; Page et al., 2019; Rahnama et al., 2006).

Previous research has assessed the EMG response of the working biceps and rectus femoris, tibialis anterior and gastrocnemius across 90-min treadmill-based soccer-specific exercise protocol (Rahnama et al., 2006). Each recording was taken for a three-min period at various speeds (6, 12, 15, and 21 km·h^{-1}) and across different measurement points (baseline, HT and immediately post 90-min). The EMG values were expressed as the root mean square (RMS) of the EMG amplitude over 10 gait cycles at each speed and measurement point. The participants' EMG activity significantly reduced as a function of exercise duration and increased in response to higher running speeds for all muscles except for the gastrocnemius. In a separate investigation, Goodall et al. (2017) assessed EMG activity of specific lower-limb muscles (biceps femoris, rectus femoris and vastus lateralis) at several time points during 120 min of free-running soccer exercise. Specifically, EMG amplitudes were taken during maximal voluntary contraction force measurements before exercise, HT, full-time and post ET; with RMS data normalised to maximal values at each time point. Significant reductions in normalised EMG values were identified for the rectus femoris at ET versus pre-exercise measures.

Electromyography amplitudes have also been assessed across three soccer-specific 90-min treadmill exercise bouts designed to simulate fixture congested periods in contemporary soccer (Page et al., 2019). In a repeated measures design, mean EMG activity was recorded in the biceps femoris across a 10-s acceleration and deceleration bout. The findings demonstrate that EMG activity decreased during many time points in the second versus the first half, and that measures in the third exercise trial were significantly lower in the biceps femoris than corresponding time points during the first trial. The EMG reductions observed were accompanied with eccentric knee flexor peak torque reductions both from pre-to-post exercise and from the first to third trial. Similar research established that a 90-min free-running simulation elicits EMG reductions in the biceps femoris from the latter 15 min of each half versus the first 15 min period, as well as concomitant decrements in knee flexor peak torque (Marshall et al., 2014). Although other studies have failed to measure EMG activity, these articles indicate that previous patterns of EMG and central motor output inhibitions correspond with fatigue-induced strength deficits (peripheral fatigue-related processes) pre-to-post soccer-specific activity (Greig, 2008; Page et al., 2020; Rahnama et al., 2003; Rhodes et al., 2019).

The above studies used different methods (simulation type, activity profiles, EMG data collection procedures and measurement timing), though the findings are indicative of inhibited muscle activation as a progression of exercise duration, in response to fixture congested schedules and post 120-min of soccer exercise. However, there is no research that has evaluated alterations in EMG amplitudes throughout 120 min of soccer-specific activity, and as such, research is required that evaluates the impact of the ET period on within-match EMG activity measures to delineate the origin of the fatigue source during prolonged periods of soccer-specific activity. Measures often used to measure the biomechanical fatigue response are isokinetic peak torque assessments and accelerometer-derived metrics, including PlayerLoad™.

1.3.2 Isokinetic peak torque

Isokinetic dynamometry is a method used to quantify muscle strength whilst resistance is applied equal to the muscular force produced and thus velocity is maintained constant throughout the range of movement (Baltzopoulos & Brodie, 1989; Dvir & Müller, 2020). Isokinetic profiling is broadly criticised for its potential lack of functional relevance in a sporting context (Croix et al., 2017), though on the other hand is considered the gold standard in muscle strength and function testing (Dvir & Müller, 2020). The most quantified isokinetic parameters are reciprocal muscle torque ratios, functional range, torque output across various angular velocities and joint angles, as well as maximal/peak torque production (Baltzopoulos & Brodie, 1989; Eustace et al., 2019; Forbes et al., 2009; Page et al., 2020). Research suggests that athletes with lower-limb agonist and antagonist muscular imbalances, such as a weakness of the knee flexors versus the knee extensors (hamstrings-to-quadriceps ratio [H:Q ratio]) may be susceptible to hamstring injury (Croisier et al., 2008; Evangelidis et al., 2016). There are two distinct H:Q ratios, which can be categorised as conventional or functional. The ‘conventional’ H:Q ratio represents the concentric hamstrings relative to the concentric quadriceps strength, whereas the ‘functional’ ratio involves the balance between knee flexor strength eccentrically and the concentric torque of the knee extensors. Researchers have argued that the functional H:Q ratio is better reflective of the synergistic function of the knee musculature during activities performed throughout soccer activity, such as sprinting and kicking activites (Evangelidis et al., 2015; Ruas et al., 2015b). Therefore, assessment of the functional ratio appears appropriate to identify the impact of fatigue-induced peak torque reductions on the risk of hamstring strain and ACL injuries (Coombs & Garbutt, 2002).

Contemporary studies have advocated metrics such as functional range for identifying modifiable risk factors for injury (Page & Greig, 2020). This isokinetic variable measures the angle over which a pre-selected percentage of peak torque can be maintained (Eustace et al., 2017). However, since there is a lack of credible scientific basis for the thresholds that are selected within the literature, the functional relevance of this measure remains unclear. To further advance understanding of the torque-angle relationship, angle-specific torque measures are reported within the literature across angular velocities ranging from 60—300 $deg \cdot s^{-1}$ (Page & Greig, 2020; Small et al., 2010). However, although angle-specific torque curves have been proposed for identifying weaknesses across specific muscle lengths (Cohen et al., 2015), they do not account for the co-activation involved with reciprocal muscle contraction (Coombs & Garbutt, 2002). In addition to these metrics, another functional consideration broadly regarded as important is the angular velocity at which isokinetic testing is performed (Eustace et al., 2017). Evidence shows that reciprocal torque ratios and absolute strength capabilities differ according to distinct angular velocities (Evangelidis et al., 2015; Iga et al., 2009). Therefore, although dynamometers measurement capabilities restrict evaluation of speeds typically associated with injury occurrence during soccer (400 $deg \cdot s^{-1}$) (Eustace et al., 2017; Nedergaard et al., 2014; Page & Greig, 2020), it is key that a range of angular velocities are tested to gain a comprehensive understanding of torque-velocity characteristics. However, despite the varying isokinetic profiling methods, peak torque is the most widely documented metric within the soccer literature (Ardern et al., 2015; Greig, 2008; Page et al., 2019; Ruas et al., 2015a; Small et al., 2010). This measure represents a single value of maximal muscle torque that can be produced during a constant pre-determined velocity, irrespective of the angle at which the peak value is achieved (Singh et al., 2002). Since soccer-specific fatigue has shown to induce reductions in peak torque (Matthews et al., 2017; Page et al., 2019; Rahnama et al., 2003; Small et al., 2010) and this measure has demonstrated the greatest reliability and lowest measurements error versus other isokinetic variables (Gleeson & Mercer, 1996; Timmins et al., 2016b), evaluation of this peak value promotes understanding of the loss of maximal strength across intermittent activity.

Over recent years, isokinetic performance measures have become increasingly common for assessment of the fatiguing impact of soccer-specific exercise (Greig, 2008; Page et al., 2020; Rahnama et al., 2003; Small et al., 2010). The thigh musculature remain the most common injury site in soccer players (Falese et al., 2016; Jones et al., 2019a); with the within-match timing of injuries demonstrating that fatigue is possibly an aetiological risk factor (Price et al., 2004; Small et al., 2010). Isokinetic strength assessments have been undertaken in amateur soccer players before, at HT and following a treadmill-based protocol designed to replicate soccer match-play (Rahnama et al., 2006). Peak torque of the dominant and non-dominant knee extensors and flexors was assessed at various angular velocities and modes of contraction (concentric [1.05, 2.09, 5.23 rad · s^{-1}] and eccentric [2.09 rad · s^{-1}]). The results demonstrated a peak torque reduction in the dominant knee extensors and flexors before exercise versus HT and further decrements from HT to post-exercise; whilst decrements in the non-dominant limb occurred from pre-to-post exercise. Another investigation evaluated peak torque of the concentric knee extensors (conKE) and eccentric knee flexors (eccKF) at isokinetic speeds of 60, 180 and 300 deg·s^{-1} acutely in response to 90 min of treadmill-based soccer-specific activity (Greig, 2008). Significant post-exercise reductions in eccKF were established at 180 and 300 deg·s^{-1} versus baseline and the initial 15-min measure. However, no significant changes were identified for conKE across all testing speeds. In a separate investigation, significant deficits in the gravity corrected peak torque values of the concentric knee extensors and flexors were observed throughout the 72 hr period following a 90 min soccer match (Ascensão et al., 2008). Therefore, the above data are indicative of fatigue-induced deficits in peak torque of major lower-limb muscles from pre-to-post 90 min simulated soccer activity, which may persist up to 72 hr post-exercise. However, little is known concerning how 120 min of soccer-specific exercise impacts peak torque characteristics or the time course of strength recovery in the days after an ET match.

Previous researchers have assessed players across three soccer-specific treadmill simulations, interspersed with 48 hr, to mimic dense scheduling in soccer (Page et al., 2019). Eccentric knee flexor peak torque measures at 60 and 300 deg·s^{-1} were recorded pre and post each trial, with significantly higher mean pre-trial values identified versus post trial across both speeds. In addition, reductions were observed in the third compared to corresponding time points during first trial for both speeds, whereas higher values were identified during trial 1 versus trial 2 for 300 deg·s^{-1}. A different study measured maximal voluntary contraction force of the quadriceps before exercise, HT, full-time and post ET of 120 min of free-running soccer-specific activity (Goodall et al., 2017). Decrements in strength were identified at HT (–11%), full-time (–20%) and ET (–27%) versus pre-exercise (baseline) values. However, although maximal voluntary contraction forces have been tested previously, isokinetic peak torque of the thigh musculature has yet to be assessed in response to 120 min of simulated soccer-specific activity and is an avenue of research required.

1.3.3 PlayerLoad™

PlayerLoad™ is a software-derived parameter, invented by Catapult Sports, a company that manufactures wearable technology (Bredt et al., 2020). There is currently a lack of clarity attached to the meaning of PlayerLoad™, due to the many misinterpretations and inconsistencies that currently exist within the literature (equations, calculations and definitions) (Bredt et al., 2020). However, it is commonly used to measure the external load profile of an athlete during exercise (Scott et al., 2013). The metric is derived from trunk-mounted global positioning systems (GPS) units housing tri-axial accelerometers designed to quantify the rate of change in acceleration movements accrued across three-planes of motion (Dalen et al., 2020). Strong positive associations have been observed between PlayerLoad™, together with session RPE (Casamichana et al., 2013), total distance covered (Gabbett, 2015) and CoD intensity (Hulin et al., 2018). Researchers have also assessed changes in PlayerLoad™ throughout simulated (Page et al., 2015) and actual soccer match-play (Barrett et al., 2016; Dalen et al., 2016).

Previous investigations have assessed PlayerLoad™ across 90 min of treadmill-based soccer-specific exercise employing standardised 15 min bouts of fixed activity (Page et al., 2015; Page et al., 2016; Page et al., 2019). All three studies established that PlayerLoad™ increases across exercise and that the vertical contribution is reduced during the latter compared with the initial 15 min of exercise. Such precise timing and planar contribution changes in PlayerLoad™ patterns are reflective of fatigue-induced alterations in running technique and movement efficiency (Barrett et al., 2014; Garrett et al., 2016). Evidence suggests that fatigue-induced losses in strength, motor recruitment and lower extremity joint couplings can compromise gait dynamics in response to prolonged running activity (Meardon et al., 2011). Therefore, it is likely that players adopt energy preservatory movements in an effort to maintain performance (Lorimer & Hume, 2014). It is speculative as to whether increasing PlayerLoad™ values reflect abnormalities in running gait; however, it is evident that the increasing planar contributions across standardised activity bouts of treadmill running represents an increased metabolic cost and perhaps a reduced biomechanical efficiency, increasing repetitive strain on soft tissues (Wilk et al., 2009).

The functional reasons for fatigue-induced injury remain unclear, although there are several changes to running mechanics that have been linked to injury that may be detectable via changes in PlayerLoad™. A study comparing running kinematics in injured and non-injured populations reported an increased trunk flexion and knee extension upon ground contact in the injured group (Bramah et al., 2018). Increases in forward lean during running is likely detectable through greater observations in the anterior/posterior plane of motion and has been linked with fatigue-related strength deficits in paraspinal and gluteal muscles (Hart et al., 2009). A greater extended knee position at landing may not be as apparent with reference to PlayerLoad™ data, though it is likely that increases in knee joint loading and breaking impulse as well as a reduced capacity to absorb impact forces during the early stance are contributing factors to knee injury (Wille et al., 2014). Another mechanism often discernible through modifications in vertical displacement is a change in vertical stiffness. Although increases in stiffness can augment performance and the utilisation of elastic energy (Maloney & Fletcher, 2018), disproportionate levels (too high or low) of lower extremity stiffness have been shown to increase injury susceptibility to soft tissues (Hughes & Watkins, 2008). Research exploring loading strategies and PlayerLoad™ patterns and its association with injury-risk, observed that certain screen tests in elite youth soccer players have shown to predict multi-axial PlayerLoad™, with links to knee injury (Bowen et al., 2019). Therefore, to date, the evidence-base appears to suggest that PlayerLoad™ and the different planar contributions are reflective of fatigue patterns and a potential increased injury risk as a function of exercise duration across 90 min of exercise. However, there remains a paucity of scientific investigations assessing PlayerLoad™ during ET, thus, it is unclear whether this additional period can further compromise movement efficiency and potentially exacerbate injury risk. Further exploration is therefore required assessing whether players are at an increased injury susceptibility during this additional 30 min period.

During sport-specific movements, such as running, smoothness is widely associated with a healthy central nervous system and is a reflection of proficient motor control and co-ordination (Kiely et al., 2019). Previous research evaluated the impact of exercise-induced fatigue on acceleration data using trunk-mounted units during running-and-cutting assessments (Cortes et al., 2014). The study found that fatigue-induced alterations in lower-limb kinetics and kinematics detracted from the smoothness of movement. In order to optimise smoothness, an athlete must minimise jerk, which is a physics concept often described as the rate of change in acceleration (Mohr & Federolf, 2021; Schot, 1978). The quantification of jerk is used to detect changes in motor control (Balasubramanian et al., 2015). Fatigue has shown to inhibit motor control and the smoothness of movement (Monjo et al., 2015), thus, it is plausible that jerk indices will increase with fatigue. However, it is not well understood if increases in jerk (reflected via increases in PlayerLoad™) can be used to quantifying fatigue of the lower limbs. Furthermore, it is unclear whether changes in the anatomical orientation of the GPS unit (scapulae or centre of mass) affects PlayerLoad™ (Barrett et al., 2014). It was determined that scapulae-placed devices underestimated jerk/PlayerLoad™ and were not as sensitive to detect changes in the vertical contribution across increasing running velocities (Barrett et al., 2014). Therefore, device placement at the upper trunk (recommended by the manufacturer to enhance GPS signals) may be questionable in relation to whether such unit positioning is sensitive enough to detect changes in the smoothness of sport-specific movements (Chambers et al., 2015). Using a device placed in a garment to measure changes in PlayerLoad™ is more feasible during match-play versus practically incompatible measurements used to infer fatigue, such as EMG and isokinetic lower-limb strength assessments. Therefore, due to the feasibility and application of PlayerLoad™ in a sporting context, it appears warranted to determine whether devices placed at the upper trunk and the changing PlayerLoad™/ jerk patterns are reflective of lower-limb muscle activation and peak torque alterations in response to soccer-specific exercise.

1.4 PHYSIOLOGICAL RESPONSES TO SOCCER-SPECIFIC EXERCISE

Applied within a soccer context, evaluations of the physiological demands have been undertaken to provide an insight into the energy requirements and metabolic profile of players to perform across an entire 90 min competitive match (Drust et al., 2007). Physiological assessments of HR, and oxygen uptake ($\dot{V}O_2$) are widely reported within the soccer literature (Alexandre et al., 2012; Bendiksen et al., 2012; Page et al., 2015) as predictions of energy expenditure. It is estimated that professional players often attain between 70—80% of their maximal oxygen uptake ($\dot{V}O_{2max}$) during competition (Bangsbo, 1994b); however, since measures of $\dot{V}O_2$ are impractical during matches (Stølen et al., 2005), these values are merely approximations. Alternatively, HR data can be collected during soccer matches to measure the physiological effort of individual players (Alexandre et al., 2012), with values reportedly ranging from 80—90% of their maximal heart rate (HR_{max}) (Bangsbo, 1994a; Krustrup et al., 2006). Some studies propose that HR can be used as an accurate reflection of $\dot{V}O_2$ output during soccer-specific exercise (Esposito et al., 2004). However, the association between HR and $\dot{V}O_2$ (i.e., the HR-$\dot{V}O_2$ relationship) appears to overestimate the energy output during soccer matches since changes in HR occur separate to alterations in $\dot{V}O_2$ (Bangsbo et al., 2007; Bangsbo et al., 2006). Additionally, the emotional stressors experienced during soccer-match play, along with the intermittent nature of soccer activity could introduce a degree estimation error and alter the linearity of the HR-$\dot{V}O_2$ relationship (Esposito et al., 2004).

Soccer elicits a greater demand on the aerobic system, with the decisive ‘game defining’ moments being largely covered through actions that rely on high anaerobic-energy turnover (Stølen et al., 2005). In soccer, BLa is often used as an indication of anaerobic metabolism energy delivery, with an average of 2—10 $mmol \cdot l^{-1}$ reached during match-play (Bangsbo, 1994a; Bangsbo et al., 2007; Krustrup et al., 2006). Although BLa values elicited are highly dependent upon the activity profile acutely before sampling (Bendiksen et al., 2012), lower concentrations are observed in the second half of soccer match-play versus the first (Stølen et al., 2005). The changes in BLa occur in conjunction with fatigue-induced reductions in running output observed during the latter phase of soccer match-play (Bradley et al., 2013; Bradley et al., 2009; Mohr et al., 2003). There is a well-documented association between the occurrence of fatigue and depletion of endogenous substrates, such as a reduced glycogen availability (Ali et al., 2007; Romijn et al., 1993). However, the exact etiology and the processes that underpin the subsequent fatigue-induced reductions in physical performance remain somewhat elusive. Considering the prolonged and highly intense activity profile of soccer (Bendiksen et al., 2012; Krustrup et al., 2006) and the high dependency of glycogen as a substrate to fuel exercise (Romijn et al., 1993), one such contributory factor proposed to cause fatigue is the gradual transition from glycolysis to fat oxidation in the event of depleted glycogen stores.

1.4.1 Substrate utilisation

Many factors regulate metabolic processes that determine which substrates are metabolised for fuelling the working muscles during exercise (Mittendorfer & Klein, 2003). It has long been established that carbohydrates and lipids primarily contribute to energy metabolism across prolonged physical exercise (Neely & Morgan, 1974). Protein (amino-acids) play a role in energy metabolism to a much lesser extent, contributing to less than 5% of energy turnover under common exercise conditions (Rose & Richter, 2009). Fatty acid oxidation dominates the energy contribution at rest and during light activity, with a simultaneous sparing of muscle glycogen (Hawley et al., 1998). At high intensities (> 65% $\dot{V}O_{2max}$), relative plasma fatty acid oxidation rates reduce, at which point the use of intramuscular triglycerides are the primary source of fatty acids for oxidation (Romijn et al., 1993). Subsequently, a greater dependence on the carbohydrate utilisation pathway becomes apparent (Armstrong et al., 2015). A key physiological explanation for the metabolic transition is the elevation in circulating catecholamines, stimulating increases in glycolytic activity and lactate accumulation, with lipolysis inhibited in the process (Clarke et al., 2011). In response to further increases in exercise intensity (~85% $\dot{V}O_{2max}$), absolute fat oxidation rates decrease (Romijn et al., 1993), with carbohydrate providing in excess of two-thirds of the energy requirements (McArdle et al., 2006).

Prolonged and extended activity durations have also shown to induce progressive increases in fat oxidation for total energy production (Achten & Jeukendrup, 2004). This progressive shift from glycolysis to lipolysis is reflective of an exercise-induced reduction in carbohydrate oxidation and net depletion in muscle glycogen (Achten & Jeukendrup, 2004). It is also important to consider that there are a complex array of factors involved with metabolic substrate patterns and usage, including, body composition, training status, environmental conditions, dietary intake and sex (Jeukendrup & Wallis, 2005; Mul et al., 2015; Ramos-Jiménez et al., 2008; Tarnopolsky et al., 1990). Although it is well established that carbohydrates and fat sources are oxidised concurrently, the relative contribution across varying exercise modes is less well established (Jeukendrup, 2003).

Directly measuring transient alterations in the utilisation of endogenous substrates is feasibly difficult across soccer-specific activity, with previous investigations using biochemical markers to infer such changes. Lower BLa and marked decreases in muscle glycogen levels have been observed after a soccer match versus pre-match values (Krustrup et al., 2006). In a separate investigation, researchers adopted the use of a 90-min soccer-specific exercise protocol to assess the impact of carbohydrate ingestion on metabolism through measures of adrenaline (epinephrine), glucose, glycerol and non-esterified fatty acids (NEFA) (Clarke et al., 2008). In the placebo condition, plasma NEFA and glycerol concentrations increased pronouncedly during the second half, with concomitant reductions in plasma glucose. Elevated adrenaline together with reductions in insulin were also identified between HT and the end of exercise at a greater rate in the placebo group. The gradual switch in energy pathway utilisation is possibly linked with an increase in adrenaline concentrations, shown to stimulate muscle glycogenolysis through the activation of phosphorylase α (Watt et al., 2001). A dampened insulin response has also shown to promote lipolysis as the hormone inhibits serine/threonine protein kinase B (also known as Akt) and stimulates the activation of protein kinase A (Choi et al., 2010). These findings are indicative that fatty acid metabolism progressively contributes to the pathway of energy metabolism as a function of exercise duration across 90 min of soccer.

Similar to previous research (Clarke et al., 2008), plasma glycerol, NEFA, blood glucose, BLa, insulin and adrenaline concentrations have been measured across 120 min of simulated match-play. Higher adrenaline, plasma glycerol, NEFA, together with lower blood glucose and BLa were identified during ET (Harper et al., 2016d; Stevenson et al., 2017). These findings support those progressive reductions in glucose concentrations, together with an increased contribution of free-fatty acids (FFA) and lipolysis are observed as the soccer-specific activity progresses into ET. The transition in substrate usage is likely a compensatory mechanism for reductions in blood glucose to promote muscle glycogen sparing and prolong the availability of endogenous carbohydrate (Burke & Hawley, 2002). Whilst these findings have merit for assessing changes in substrate utilisation across prolonged soccer-specific activity, the measures used are merely indirect estimates of the metabolic demands of players. Indirect calorimetry measurements remains widely considered the gold standard for quantifying substrate oxidisation (Gribok et al., 2016). Therefore, using indirect calorimetry techniques to measure instantaneous gas exchange rates, such as the respiratory exchange ratio (RER) appears warranted to provide more accurate representations of fuel usage patterns throughout 120 min of soccer-specific exercise.

1.4.1.1 Respiratory exchange ratio

The RER refers to the direct measurement of O_2 utilisation and CO_2 production and can be used to estimate the metabolic contributions of carbohydrate and lipid oxidation (Jeukendrup & Wallis, 2005). The RER can also be adopted for estimating the point of exercise exhaustion (i.e., value ≥1.1) (Goedecke et al., 2000) and anaerobic thresholds (Solberg et al., 2005). The relative contribution of protein is unable to be derived from respiratory gases, and nor is the precise proportion of oxidised carbohydrate (plasma glucose and muscle glycogen) and lipid forms (plasma fatty acids and intramuscular triglycerides) able to be determined (Armstrong et al., 2015). To provide context, assuming protein contribution is negligible, a RER of 1.0 suggests entirely carbohydrate is being utilised for exercise, whereas 0.70 is indicative of total lipolysis. Therefore, 0.85 is indicative of an equal contribution of each of these metabolic pathways (Melzer, 2011). However, there is large interindividual variability in resting RER that persists during exercise of increasing intensity. There are also several determinants that impact RER, including, the amount of glycogen stored in skeletal muscle, training volume, fibre type distribution, and diet (Goedecke et al., 2000).

Estimating metabolic fuel usage using RER has been conducted across varying populations, such as trained cyclists completing differing intensities (Goedecke et al., 2000), trained males completing a single bout of aerobic and resistance exercise (Jamurtas et al., 2004) and trained and untrained males performing a maximal graded ramp test (Ramos-Jiménez et al., 2008). The whole body carbohydrate and fat oxidation rates of 16 professional soccer player has also been estimated using indirect calirometry with RER (≥1.1) used an an indicator of volitional exhaustion during a graded treadmill ramp exercise test (Randell et al., 2019). Another study utilised RER measurement procedures as an indicator of fuel metabolism during various exercise modes in youth soccer players (Castagna et al., 2006). It was reported during this investigation that the Yo-Yo Intermittent Endurance Test (YYIET) Level 1 and an incremental treadmill test elicited similar RER values, suggesting a similar fuel usage between tests. A separate study compared the RER at $\dot{V}O2_{max}$ between the 20 m multistage shuttle run test, YYIET Level 1 and a progressively increasing treadmill test to volitional exhaustion (Aziz et al., 2005). The maximal treadmill test elicited the highest RER at exhaustion (1.16), with the multi-stage fitness test (1.10) being significantly greater than the YYIET 1 test (1.05).

The RER of 12 youth soccer players has been assessed across 3 x 14 min bouts of a soccer-specific exercise protocol performed on a non-motorised treadmill (Oliver et al., 2007). Although RER data were not provided for the first bout of exercise, no differences in mean values were reported for bout two (0.89) and three (0.90). Another study adopted the LIST to evaluate the impact of a carbohydrate-electrolyte ingestion on RER and soccer skill performance across an entire 90-min period (Ali & Williams, 2009). The RER reduced as a function of exercise duration in the placebo condition, with values at 75—90 min falling below 0.85. This suggests that fat oxidation has a greater contribution to overall substrate usage during the latter 15 min of simulated soccer exercise. This is supported by the blood analyses in the same study, whereby plasma FFA increased with concomitant reductions in plasma glucose at 90 min compared to 60 min of the free-running protocol. This research was one of few studies to assess RER throughout dynamic exercise simulating the intermittent demands of match-play. However, although it appears that there is a gradual switch in substrate metabolism (glycolysis to lipolysis) across 90 min, which is exacerbated towards the latter stages of this duration; gaseous exchange data has yet to be taken across 120 min of soccer-specific exercise. Therefore, it remains unclear the extent to which competing in an ET period effects the utilisation of metabolic substrates in participants strictly limited to water ingestion and exercising in the absence of exogenous carbohydrate.

1.4.2 Differential ratings of perceived exertion

Evolutionary technological advancements (e.g., GPS and semi-automatic multiple-camera systems) now facilitates the accurate monitoring of training and match loads (Carling et al., 2008; Page et al., 2015). The detailed external load data retrieved from such sophisticated systems (total distance, high-speed running, sprinting etc.) can be applied by sports scientists and practitioners to minimise the occurrence of fatigue, overreaching, and injuries/illness (Drew & Finch, 2016; Gabbett, 2016). However, exploring an athletes' relative internal load to a given external stressor is integral to gaining a comprehensive depiction of perceived exertion and accurately prescribing post-match recovery and training strategies (Weston et al., 2015). One such internal load measure that is universally adopted within the sport and exercise literature to objectively quantify a subjective interpretation is RPE. From a historical perspective, RPE was originally developed and applied by the Swedish psychologist, Gunnar Borg (Borg, 1970). The simplistic approach involves an individual providing scale ratings based on their perception of effort during exercise (Groslambert & Mahon, 2006). The method was initially pioneered to compliment physiological stress indicators using quantifiable measures (Foster et al., 2021), with research since demonstrating that RPE correlates well with several objective markers of training load and possesses good criterion validity (Chen et al., 2002).

Different variations of the RPE method were later established, which included session RPE (Foster et al., 1995). Session RPE is a valuable technique for measuring the overall internal load acquired across the entire duration of a training session (McLaren et al., 2016; McLaren et al., 2017), but lacks sensitivity to assess acute changes in momentary exertion and training load (Macpherson et al., 2019). Whilst RPE is praised for its simplicity, critics have argued that the generalisation of exertional perceptions obtained by a single rating may not be a sensitive means of discriminating between a range of specific sensory mediators. For this reason, d-RPE has been proposed as a precisional measure capable of distinguishing between discrete aspects of exertion to provide a well-rounded evaulation of internal loads across exercise (Weston et al., 2015). Acknowledging the existence of many variations of this method (e.g., technical, upper-body, cognitive), researchers interested solely in the physical perceptions of effort in soccer, may choose to distinguish between lower-body muscle exertion (RPE-L), central/breathlessness (RPE-B) and overall (RPE-O) ratings of exertion (Barrett et al., 2018; Macpherson et al., 2019; McLaren et al., 2016; Weston et al., 2015). Given the scenario whereby the exertional perceptions for RPE-L are reported consistently high, the athlete may be experiencing mechanical strain on the skeletal leg muscles (quadriceps, hamstrings, calves etc.), thereby, confirming the prescription of leg-specific strength or endurance training (Macpherson et al., 2019). On the other hand, RPE-B may correspond to an increased central demand on breathing rate and/or heart effort, thus, a greater training emphasis can be placed on the pulmonary and cardiovascular system (McLaren et al., 2020). Therefore, given that the activity profile of soccer activity encompassess a variety of physical demands (Carling, 2013; Dellal et al., 2011a), capturing a detailed internal load profile may assist practitioners with prescribing appropriate training programmes that isolate between different dimensions of effort to identify and target discrete components of fitness.

Assessments of d-RPE have been undertaken across many populations, including professional team sport athletes (McLaren et al., 2018; McLaren et al., 2017), soccer referees (Castillo et al., 2017), as well as female (Wright et al., 2020) and youth soccer players (Gil-Rey et al., 2015; Salter et al., 2020). Contemporary analyses of 20 youth soccer players over a 46-week season demonstrated that d-RPE is positively correlated with several external training load metrics (Maughan et al., 2021). Weston et al. (2015) were the first to examine the application of d-RPE as a measure of internal load in team sport athletes. This seminal work involved collecting d-RPE from Australian League Football players to assess the associations between GPS-derived metrics and the distinct sensory inputs of d-RPE. The findings suggest that the largest associations were observed for RPE-L and that overall, d-RPE possesses the discriminatory capabilities required to differentiate between dimensions of effort. Another study investigated the impact of positional role and contextual variables on reported d-RPE in 32 English Premier League players across an entire season (Barrett et al., 2018). It was established that full-backs report the highest d-RPE ratings, with increases observed when the match was competed against higher league opposition. More recently, an exploratory investigation was carried out to assess the agreement of an experienced UEFA A License coach and 16 semi-professional soccer players' perceptions of training load and intensity using d-RPE and session RPE across seven different training sessions over a six-week period (Macpherson et al., 2019). Although it was highlighted that player–coach agreement was not present for session RPE, evidence of agreement was found for d-RPE. Therefore, d-RPE appears to be a useful measure for differentiating training load and intensity as players and coaches can focus on specific aspects of training exertion. The studies above all measured d-RPE after a training session or match, with limited knowledge as to the changing perceptions of d-RPE across soccer-specific exercise. Therefore, given the application, sensitivity and practicality associated with d-RPE, and the requirement for applied and controlled research in soccer, further understanding of the extent to which transient changes in internal perceptions of load occur across soccer activity is required.

Since the early design of the Borg 15-point (6—20) linear scale (Borg, 1970), alternative scales have been proposed, which includes the Borg CR10® scale (or 'centiMax' scale) (Borg, 1998) and Borg CR100® scale (Borg & Borg, 2002). Critics have argued that the Borg CR10® scale fails to present sufficient rating options to be considered sensitive to detect slight changes in perceived exertion (Pageaux, 2016). Accordingly, the more fine-graded Borg CR100® scale was developed (Borg & Borg, 2002), but anecdotal observations suggest that this may still be considered less interpretable than the classic 15-point Borg scale. The 6—20 linear scale remains commonly employed within contemporary soccer literature (Coppalle et al., 2019; Ferraz et al., 2018; Owen et al., 2016), perhaps because it increases linearly with HR and $\dot{V}O_2$ and can be used to monitor effort perception as it reflects changes in objective measures of HR (Borg, 1998). For instance, a score of 6 reflects 60 bpm, which equates to the verbal anchor 'no exertion at all', whereas a value of 20 resembles 200 bpm, resembling a scale rating of 'maximal exertion'. As such, this provides a reference point by which the participant can relate when scoring their perceived exertion. The scale has also demonstrated linear correlations with HR, oxygen uptake and power output in response to increasing exercise intensities during running (Cabral et al., 2020; Eston et al., 1987; Lamb et al., 1999). Utilising the Borg 15-point scale in conjunction with d-RPE may enhance understanding of the distinct physiological loading patterns imposed on players across 120 min of soccer-specific exercise. Applying the Borg 15-point scale to measure acute changes in d-RPE across soccer-specific exercise also provides a novel contribution to the literature.

1.5 RECOVERY FOLLOWING SOCCER-SPECIFIC EXERCISE

The within-match activity performed during soccer may cause temporary (i.e., instantly debilitated in response to an acute task) and cumulative fatigue (i.e., an accumulation of repetitive strain) impairing subsequent physical performance (Mohr et al., 2005). In order to limit the negative implications for injury and illness associated with residual fatigue (i.e., amassed fatigue that persists into the next match), optimal recovery must be achieved before the next competitive encounter (Mohr et al., 2005; Nédélec et al., 2012, 2013; Page et al., 2019; Silva et al., 2018). Recovery (herein defined as the restoration of homeostatic balance) is a regenerative process, whereby considered from a practical perspective is the return of the player back to their initial pre-performance state (Nédélec et al., 2012). To track the recovery response to post soccer-specific exercise, numerous recovery-related markers are used to gain insight into the recovery profiles of players. Since no marker in isolation can provide sufficient information as to the status and time course of recovery following soccer, it is important to monitor various markers to achieve a comprehensive picture of recovery.

1.5.1 Markers of recovery

A number of markers have been used to assess recovery in response to simulated soccer-specific protocols and match-play (Nédélec et al., 2012; Silva et al., 2018). The markers used can be categorised as either direct or indirect. Direct methods have included repeated collection and analysis of muscle biopsy samples. Indirect methods have involved assessing changes in biochemical efflux of myocellular enzymes and proteins, subjective measures of perceived muscle soreness, muscle function and strength characteristics, and functional performance measures. Such comprehensive summaries of the markers used to assess recovery in response to soccer are available (Nédélec et al., 2012, 2013; Silva et al., 2018), however, such information is beyond the scope of this thesis. Instead, the purpose of the current section is to present a brief summary of the markers adopted to examine recovery in certain chapters throughout the thesis.

1.5.1.1 Biochemical markers

Soccer involves many activities that require eccentric muscle contractions, such as sprinting, jumping, kicking, and decelerating, known to increase biochemical markers of inflammation, oxidative stress and muscle damage (Ascensão et al., 2008). The release of abnormally high levels of serum concentrations of intracellular proteins are widely regarded as adequate indicators of muscle damage such as CK, creatinine and aspartate aminotransferase (AST) (Lippi et al., 2008; Pundir et al., 2019). Soccer has also shown to induce elevations in biochemical markers of metabolic stress, including urea, versus other intermittent team sports (Souglis et al., 2015). Therefore, it is important that a wide array of biochemical markers are investigated to determine the underlying physiological changes during the regeneration processes (Nédélec et al., 2012), since there is no biochemical marker in isolation that can provide an extensive picture of muscle damage recovery following soccer-specific activity.

1.5.1.1.1 Creatine Kinase

Increases in plasma activity of intramuscular proteins are often indicative of myofibrillar damage and increased permeability of the sarcolemma (Howatson & Van Someren, 2008). Creatine kinase is a biochemical marker frequently used within soccer to estimate the magnitude of intracellular damage (Lazarim et al., 2009; Russell et al., 2015a). Disruption to skeletal muscle fibres can lead to intramuscular proteins, such as CK, leaking into the blood (Baird et al., 2012). However, although CK is commonly used in soccer due to the size of the increase being higher compared with other proteins, the validity of the marker as a surrogate for muscle damage is contentious (Thompson et al., 1999; Warren et al., 1999). For instance, some athletes are non-responders (i.e., demonstrate comparatively small changes in CK activity) and muscle adaptations can occur following unaccustomed eccentric exercise (Clarkson & Tremblay, 1988). It is also apparent that the extent of exercise-induced CK efflux is largely dependent on individual characteristics (i.e., genetics, sex, training status and fibre type composition) and exercise stimulus (i.e., type, intensity, duration/volume and muscle groups used) (Baird et al., 2012). Following 90 min of simulated and actual match-play, CK levels often peak at 24—48 hr (Malone et al., 2018; Nedelec et al., 2014; Nédélec et al., 2012; Russell et al., 2015a; Russell et al., 2016; Silva et al., 2013). Increases from baseline (+70 to +250%) have been observed post soccer-specific exercise with absolute values reaching more than 900 $U{\cdot}L^{-1}$ before returning to baseline between 48 and 120 hr (Ascensão et al., 2011; Ascensão et al., 2008; Nédélec et al., 2012). As it is expected that an increased duration and volume of exercise will elevate CK activity (Nédélec et al., 2012), an ET period may further inflate the CK response due to the elongated exercise stimulus. A previous investigation exploring five English Premier League reserve team players, found an elevation in CK activity at 24 and 48 hr post 120 min matches versus baseline (Russell et al., 2015b). However, there was no direct comparison to 90-min matches, and as such, the extent to which the addition of ET affected recovery remains equivocal. A later study examined the CK response in players that competed in three matches, with the middle of the three progressing to ET (i.e., 90, 120, 90 min) (Winder et al., 2018). The researchers found no significant changes in CK following the ET match versus either of the 90-min matches. Therefore, due to the ambiguous results and the limitations that existed in these studies, such as small sample sizes, lack of dietary control and inherent variability between matches; investigating the CK response following both 90 and 120 min of soccer-specific activity in the same group of players is required. Limitations also exist with CK including most notably the high inter-individual variability even among similarly trained cohorts (Paulsen et al., 2012; Urhausen & Kindermann, 2002). For instance, reference intervals have been provided based on the analysis of CK values in 186 male soccer players over a 10 year period (Mougios, 2007). To be eligible for the study, players had to be healthy, have no known diseases or major injuries, and not taking prescription drugs during the week preceding blood sampling; but no exercise controls were placed on participants. Lower reference limits were 82 $U \cdot L^{-1}$ (95% CI: 72—86 $U \cdot L^{-1}$) and upper reference values were 1083 $U \cdot L^{-1}$ (881—1479 $U \cdot L^{-1}$), thus indicating the disparity between athletes of a similar training level. As such, CK evaluation must be accompanied with additional measures to provide a more extensive assessment of biochemical activity and the recovery response, such as, other markers indicating protein degradation.

1.5.1.1.2 Creatinine

Creatinine is a waste product of creatine phosphate derived from protein and muscle breakdown (Nowakowska et al., 2019). Serum creatinine measures are accepted in clinical medicine as indicators of renal function (Banfi & Del Fabbro, 2006b) and widely used in sports medicine as a gauge of water-electrolyte balance and general health status (Nowakowska et al., 2019). Blood creatinine concentrations are notably higher in athletes with a greater muscle mass than the general population (Banfi & Del Fabbro, 2006a, 2006b; Silva et al., 2006), due to the increased creatine turnover (Banfi & Del Fabbro, 2006a; Colombini et al., 2014). The common reference interval for the general population is considered 62–115 $\mu mol \cdot l^{-1}$, (Banfi & Del Fabbro, 2006b), whereas soccer players have shown to exceed 115 $\mu mol \cdot l^{-1}$ and reach levels of up to 135 $\mu mol \cdot l^{-1}$ at various stages in a competitive season (Anđelković et al., 2015). Research tracking recovery in soccer players found that creatinine activity remains unchanged across an entire competitive season (Stone et al., 2011), whilst another study demonstrated increases in midfield players throughout the season (Nowakowska et al., 2019). Similarly, levels of creatinine have shown to be elevated throughout certain time points during 3—6 months of a season (Anđelković et al., 2015; Huggins et al., 2019; Silva et al., 2008). Acute measures of creatinine taken after 90 min matches suggests that activity of this marker is increased acutely versus baseline activity (Colombini et al., 2014); however, whether this marker is further impacted upon by 120 min of soccer-specific exercise remains to be investigated.

1.5.1.1.3 Urea

Urea is the major end-product of amino-acid oxidation (i.e., produced from the conversion of ammonia) (Lemon, 1994) and taken together with CK can represent an acute reduction in exercise tolerance (Urhausen & Kindermann, 2002). Elevated levels of serum urea are associated with an enhanced protein degradation and stimulated gluconeogenesis due to training-related stress, increases in load and volume, and a longer duration of intensive endurance exercise (Haralambie & Berg, 1976; Manna et al., 2010; Meyer & Meister, 2011; Urhausen & Kindermann, 2002). Systemic concentrations of urea have been postulated to implicate an index of adaptation to training with low urea indicating the need for an increased exercise stimulus, whereas, reported high levels may require a tapered exercise regime

(Manna et al., 2010; Nowakowska et al., 2019). However, it is also recommended that nutritional factors be taken into consideration alongside measurements of urea (Urhausen & Kindermann, 2002). Increased ingestion of dietary protein intake has been linearly associated with urea production (Young et al., 2000), thus, dietary controls may be imposed to increase the validity and reliability of measures. Significant increases in urea have previously been observed following matches compared with pre-match values in both elite female (Andersson et al., 2008) and male soccer players (Colombini et al., 2014). Likewise, urea values have shown to peak acutely following a 90-min soccer match and remain elevated up to 37 hr (Souglis et al., 2015). Since increases in exercise volume and duration are associated with increases in urea (Haralambie & Berg, 1976; Meyer & Meister, 2011), it is credible to assume that competing in an ET period may result in further breakdown of structural proteins. However, to date, no studies have assessed urea post 120 min of soccer-specific exercise.

1.5.1.1.4 Aspartate aminotransferase

Aspartate aminotransferase (AST), formerly known as serum glutamate oxalate transaminase or abbreviated as SGOT; is an enzyme used to indicate the degree of myofibril damage, such as in response to exercise (Valentine, 2017). However, AST is also present in liver and subsequent damage to this organ can result in an increase in serum activity, potentially limiting its validity (Huang et al., 2016). Exercise studies have traditionally utilised this marker alongside alanine aminotransferase, although AST appears to be more sensitive in reflecting the magnitude of muscle damage (Hoffman et al., 2002; Koutedakis et al., 1993; Leppänen, 1989). It is well established that marked intra-individual diurnal differences in AST levels exist (Hammouda et al., 2012; Kentiba et al., 2019), thus confirming the need for exercise conditions to be conducted at the same time of day if concentrations of AST are to be comparable. Discounting individual exceptions, resting AST values for a healthy person are approximately 24 $\mu \cdot L^{-1}$ (Banfi & Morelli, 2008). Baseline values for soccer players have been reported as 25 $\mu \cdot L^{-1}$ and the same group of players reaching in excess of 34 $\mu \cdot L^{-1}$ following exercise (Trajković et al., 2018). Longitudinal observations of professional soccer players identified a reduction in AST throughout the competitive season (Nowakowska et al., 2019). Significant temporal increases have also been observed immediately after a 90-min match for players compared to pre-performance values (Hoffman et al., 2002). However, the impact of the additional ET period on AST activity has yet to be researched and is an avenue worthy of exploration.

1.5.1.2 Subjective measures of perceived muscle soreness

Muscle soreness is a marker commonly used to assess discomfort and pain, often experienced in response to excessive and unaccustomed exercise loads (Cheung et al., 2003). Subjective muscle soreness assessments are used in contemporary applied settings alongside other objective measures (Thorpe et al., 2015), thus, there is a great need for a balance of easily applied tests and rigorous laboratory assessments in soccer science research. Muscle soreness appears to develop 6—24 hr post-exercise, increasing progressively at 24—72 hr (Ascensão et al., 2011; Rey et al., 2012). Depending on the extent of soreness, the symptoms typically subside and dissipate 5—7 days following the cessation of exercise (Cheung et al., 2003; Valle et al., 2013). There are several methods to measure perceived soreness subjectively including the VAS and pain pressure threshold (PPT) assessments.

1.5.1.2.1 Visual Analogue Scale

A commonly used method of evaluating perceived muscle soreness is the VAS (Fanchini et al., 2015; Page et al., 2019). Variations of the scale exist, though typically this assessment involves an individual indicating their perceived degree of soreness on a spectrum with descriptors *no soreness* and *unbearably sore* at contrasting points of a 100—200 mm continuum (Howatson et al., 2012; Paulsen et al., 2010). Traditionally, ratings have been provided while a relaxed state is maintained, whilst participants adopt a static position (Williamson & Hoggart, 2005). Other methodological variations involve holding a squat position whilst indicating perceived soreness levels (Howatson et al., 2012; Page et al., 2019), or even providing scores in response to palpating specific muscles (Paulsen et al., 2010). The simplistic nature of this method and the fact it is easily administered and sensitive makes it an appealing strategy for quantifying soreness (Chiarotto et al., 2019). This approach to measuring soreness has been used for soccer-specific investigations in response to training sessions (Fanchini et al., 2015) and 90 min of simulated and actual match-play (Ascensão et al., 2008; Krustrup et al., 2011; Magalhães et al., 2010; Page et al., 2019), although has yet to be used to assess recovery following 120-min of soccer-specific exercise.

1.5.1.2.2 Pain pressure threshold

Pain pressure threshold is another measure often used to assess perceived muscle soreness. The PPT method involves the researcher applying progressively increasing force to the resting limb of a participant until the point at which the sensation of pressure becomes pain (Aboodarda et al., 2015). A handheld algometer with a flat headed cylindrical probe is applied perpendicular to the muscle belly and the reading taken from the strain gauge attached to the instrument is recorded in newtons, kilograms or pounds (Clifford et al., 2016b; Sands et al., 2015). The PPT test has been used frequently to investigate recovery post exercise-induced muscle damage (Casanova et al., 2018; Dannecker et al., 2012; Rezaei et al., 2014), and to assess soccer players from a sports medicine and rehabilitation perspective (Madeleine et al., 2014; Martin-Alguacil et al., 2019; Navarro-Santana et al., 2019), though is not commonly used to assess recovery following soccer-specific exercise. However, despite using non-soccer-specific activity models, monitoring responses to other exercise modalities has reported that muscle soreness can last up to and beyond 72 hr after eccentric-biased exercise (Clifford et al., 2016a; Clifford et al., 2017). Therefore, given the paucity of literature profiling PPT in response to a soccer-specific stimulus, rigourous PPT measures of recovery following soccer-specific exercise are required.

1.5.1.*2.3* Summary

Muscle soreness may increase injury susceptibility due to pain perceptions and subsequent adjustments in running strategies (Smith, 1992), as well as the impact on individual effort (Fletcher et al., 2016). This may in-turn prevent adherence to soccer training and subsequent performance potential, and as such, should be considered a useful tool for monitoring recovery. It appears that the symptoms of muscle soreness are not entirely reflective of the magnitude of change observed in other indirect muscle damage markers and recovery, such as, but not limited to CK efflux and muscle function (Clarkson & Hubal, 2002; Duffield et al., 2008; Hyldahl & Hubal, 2014; Nosaka et al., 2002). Therefore, it can be concluded that using a VAS and PPT tests to assess soreness is not sufficient to comprehensively reflect recovery and should be considered together with other indirect markers including biochemical markers and muscle function.

1.5.1.3 Muscle function

Muscle function can be considered the maximal force or power capacity of skeletal muscle and due to the applicability of the measure is widely considered important for assessing athletic populations (Enoka & Duchateau, 2008; Paulsen et al., 2012). Measures of muscle function, such as jump performance, are key determinants of success in soccer (Arnason et al., 2004; Nédélec et al., 2012) and can be used as a surrogate for a player's ability to leap to challenge for heading the ball. Jump indices are used within the literature potentially because they are most relevant as they can easily be extrapolated to soccer (Nédélec et al., 2012, 2013). Vertical jumping activities, specifically the CMJ and reactive strength index (RSI) are measures that can be used to assess changes in muscle function (Nédélec et al., 2012). Exercise-induced fatigue may reduce muscle function, and thus, one of the principal goals of recovery is to return optimal muscle function as prompt as achievable. Monitoring such changes in these indices are, therefore, pertinent for assessing the development of fatigue and the subsequent recovery response in soccer players.

1.5.1.3.1 Countermovement jump

The CMJ is a dynamic movement involving several muscle groups working in concert and is a favoured diagnostic tool used in soccer to assess whether players are physically ready to meet match demands (Andersson et al., 2008; Krustrup et al., 2010; Nédélec et al., 2012).

Previous investigations have identified that simulated and actual match-play have deleterious effects on CMJ height up to 48 hr (Bailey et al., 2007), and persisting until 72 hr (Ascensão et al., 2010; Thomas et al., 2017). Aside from the functionality and translational potential of the CMJ, it is quick and easy to implement, and can also be used to assess impairment of the stretch shortening cycle (SSC) (Andersson et al., 2008). The SSC involves the muscle being stretched immediately prior to contraction whereby part of the energy is stored and reused, producing a more powerful contraction versus a concentric action in isolation (Flanagan & Comyns, 2008; Komi, 1992). This measure of elastic energy storage capacity is also strongly associated with exercise-induced fatigue (Barker et al., 2018; Pierrynowski, 2007). Soccer involves many activities that require an eccentric-to-concentric component such as jumping, kicking, tackling and sprinting (Billot et al., 2010); as such, this measure is reflective of the change in physical performance capacity relative to soccer. However, soccer requires plyometric movements that are performed at high speed including CoD and agility tasks which may be better reflected by the rebound capacity of an athlete derived through evaluation of an athletes RSI (Ebben & Petushek, 2010; Lloyd et al., 2009).

1.5.1.3.2 Reactive strength index

The RSI assessment is adopted to quantify the synergy between jump height and ground contact time typically measured during an incremental drop jump (Ebben & Petushek, 2010). This measure is an assessment of an athletes ability to reverse an eccentric to concentric movement instantaneously by minimising ground contact time, and is characterised as the development of maximal force output in the minimum amount of time (Ebben & Petushek, 2010; Lloyd et al., 2009). The RSI originated from the Australian Institute of Sport as an element of the Strength Qualities Assessment Test (Wilson et al., 1991) and has since been adopted in a practical strength and conditioning environment (McClymont, 2003). Assessing RSI is less conventional in soccer research perhaps given its logistical measurement difficulty compared with CMJ, though is the only practical jump assessment with an identifiable ground contact time (Ebben & Petushek, 2010). This measure has been used in soccer studies assessing the effects of plyometric training on various jump indices (Ramirez-Campillo et al., 2014; Ramírez-Campillo et al., 2015a; Ramírez-Campillo et al., 2015b), and the impact of both non-nutritional and nutritional interventions on recovery post 90 min of soccer match-play (Abbott et al., 2019; Abbott et al., 2018a; Brownstein et al., 2017). When considered from a recovery perspective, RSI appears compromised for between 24—48 hr post both 90 min simulated soccer-specific activity and matches (Brownstein et al., 2017; Thomas et al., 2017). However, the influence of 120 min of soccer-specific exercise on this dynamic performance characteristic remains to be investigated. This information would provide practitioners with an applied method of tracking neuromuscular function in the time-period following ET matches.

1.5.2 Time course of recovery

Post-match fatigue is often characterised as a reduction in physical performance during which the recovery process begins to return players to pre-match performance capacity (Bishop et al., 2008; Nédélec et al., 2012). An inadequate recuperation duration during periods of fixture congestion (i.e., two or three matches per week for several weeks), can have negative implications for performance (Carling et al., 2015; Dellal et al., 2015; Page et al., 2019) and injury (Dupont et al., 2010; Ekstrand et al., 2016; Hawkins et al., 2001; Page et al., 2019). For instance, professional players who competed in two matches per week were 6.2-fold more likely to sustain an injury versus those who competed in one match per week (Dupont et al., 2010). It was also reported that players who were classified as underperforming at the 2002 FIFA World Cup had completed an average of 12.5 matches in the 10-week period leading up to the competition, whereas, those who exceeded expectation had played nine matches over the same period (Ekstrand et al., 2004). In this section, the time course of the recovery profile of soccer players will be reviewed with pre-eminent focus given to the markers considered above.

Ascensão et al. (2008) investigated the time course of recovery following a single 90 min competitive match using measures of plasma CK, perceived muscle soreness (using the VAS), 20 m sprint ability and conKE and eccKF. Like the CK data, elevations in muscle soreness were identified until 72 hr post-match. The authors also found that sprint ability and knee extensor peak torque remained impaired up to 72 hr. Similar research was conducted by Ispirlidis et al. (2008), using assessments of CK, VAS muscle soreness measures, and vertical jump height, among other variables, up to one week following a 90 min elite soccer match. Peaks in CK were observed at 48 hr, returning to baseline at 120 hr. Muscle soreness peaked at 48 hr, though was restored 72 hr post-match. Jump performance was significantly reduced at 24 hr though returned to baseline by 48 hr. Increases in CK and muscle soreness, and decrements in CMJ were identified for the entire 72 hr recovery period. While acknowledging the high ecological validity associated with match-play (Russell & Kingsley, 2011; Russell et al., 2011b), the effect of the homeostatic disruptions and fatigue responses might change according to the variability of the activity profile (Greig et al., 2006). Therefore, match-play does not offer a sustainable mode of exercise and, as such, soccer-specific protocols are used to standardise player output and avoid different physical loads experienced by the player to elicit repeatable responses (Page et al., 2015; Page et al., 2016; Page et al., 2019).

Several studies have directly compared the recovery response elicited by match-play with soccer-specific exercise protocols using the same population of players reporting similar physiological responses and activities (Bendiksen et al., 2012; Magalhães et al., 2010; Russell et al., 2011b). Firstly, Magalhães et al. (2010) compared the recovery response elicited by the LIST (Nicholas et al., 2000), with recovery in the 72 hr period following match-play. The authors identified that neither CK, perceived muscle soreness, CMJ height nor knee extensor and flexor peak torque were influenced by exercise condition (i.e., match-play *vs* simulation). Time effects existed for each variable across all time points for the 72-hr period irrespective of the mode of exercise. Bendiksen et al. (2012) assessed the impact of competitive match-play and the CST on plasma CK activity in the 48-hr following exercise. The CK values were 200 ± 21 $U \cdot L^{-1}$ immediately post and 324 ± 76 $U \cdot L^{-1}$ at 24 hr after the competitive match. The values after the CST were 229 ± 48 $U \cdot L^{-1}$ and 312 ± 57 $U \cdot L^{-1}$ immediately post and 24 hr following, respectively. Therefore, no differences were found between simulated and actual match-play, thus, supporting the use of simulations to assess the time course of recovery. The free-running simulations discussed above attempted to recreate the within-match exercise patterns, though may fail to prevent pacing, and ultimately lack experimental control over player physical performance metrics. This exercise model thereby, may be replaced with treadmill-based protocols due to their capacity to standardise player activity (Page et al., 2015) as the exercise stimulus and magnitude of fatigue may influence the time course of the recovery response (Nédélec et al., 2012).

A 90-min non-motorised intermittent simulation has previously been used to assess the recovery time course of professional players (Nedelec et al., 2013). The findings suggest that CMJ height remains impaired for 72 hr, while significant increases were observed for muscle soreness and CK up to 24 hr post exercise. However, no differences from baseline persisted until 24 hr or beyond for any other recovery parameters including squat jump, repeated sprint ability, perceived sleep quality, levels of fatigue or isometric squat peak force, thus, outlining the sensitivity of CMJ, muscle soreness and CK in capturing post-match fatigue and changes in recovery. Greig (2008) assessed peak torque of the conKE and eccKF at isokinetic speeds of 60, 180 and 300 $deg \cdot s^{-1}$ in response to a 90-min motorised treadmill-based protocol. Decrements in peak torque of the eccKF were observed at various isokinetic speeds at the end of the match versus baseline and measures taken after 15 min of exercise. However, although reductions in isokinetic variables may have persisted for an extended post-match period, measures were not taken across the days following the soccer-specific protocol to assess player recovery. A motorised treadmill-based protocol has also been utilised to assess the effect of fixture congested period on residual fatigue and the physical performance responses of players (Page et al., 2019). Increases in muscle soreness and deficits in eccKF peak torque at 60 $deg \cdot s^{-1}$ were observed after the third match versus the first match, whilst knee flexor peak torque at 300 $deg \cdot s^{-1}$ was reduced in the second and third match versus the first match. These data suggest that a 48-hr period separating matches may not be sufficient for the recovery of subjective markers and muscle strength, though no recovery measures were taken during the intervening period between matches. However, researchers have yet to investigate the time course of recovery in response to both 90- and 120-min treadmill-based soccer-specific exercise and thus, direct comparisons of the same cohort of players are required in response to both exercise durations.

1.6 THE USE AND APPLICATION OF SURVEY RESEARCH TO FACILITATE EVIDENCE-BASED PRACTICE IN SOCCER

A survey is an instrument comprised of a series of questions used to collect information often from a representative sample of a population (Robinson & Leonard, 2018). Online surveys are often employed to reach a large number of respondents, since there is a reduced requirement for contact time versus interviews, focus groups and other methods of qualitative data collection (Harper & McCunn, 2017). However, to reduce the time burden and, as such, increase response rate, careful consideration must be applied to the number of questions and the time required for survey completion (Wright & Schwager, 2008). The survey design often takes a qualitative or quantitative approach to data collection, with advocates arguing that a mixed methods stance (i.e., both qualitative and quantitative) allows a broader understanding of a research question than does the adoption of a single method in isolation (Wei & Lin, 2017). Using a mixed methodological approach involves questions that are both open (typically facilitating a more detailed response) and closed (typically answered with a single word or multiple-choice options) to provide a wide range of responses for analyses (Harper & McCunn, 2017). Maintaining participant anonymity is another important consideration of survey design to avoid potential bias and facilitate authentic responses (Grimm, 2010). Therefore, adopting the use of anonymous online surveys seems appropriate to enable truly reflective feedback and allowing individuals to voice their concerns as to how research can be conducted in the best interest of their practice (Harper & McCunn, 2017).

Over recent years, there has been a widespread adoption of survey research in soccer to investigate the difference between coaches' and practitioners' perceptions of training load monitoring (Weston, 2018), return-to-play practices after hamstring injury (Dunlop et al., 2019), the occurrence of mental fatigue in youth players (Thompson et al., 2020), how feedback of GPS data supports decision-making (Nosek et al., 2021), and practitioners' views on substitutes (Hills et al., 2020) and the ET period (Harper et al., 2016c). These studies have primarily involved academics and applied sports scientists retrieving data from coaches and practitioners operating within the field. However, contemporary survey analyses have collected survey responses from players (Nosek et al., 2021; Thompson et al., 2020), with this process perhaps promoting player buy-in, given a lack of training monitoring feedback provided to athletes has shown to result in disengagement with practice (Neupert et al., 2019). The feedback received from a survey can be applied in a variety of different ways, such as to determine the current practices and behaviours that are being adopted within the sporting domain (Harper et al., 2016c; Nosek et al., 2021). Equipped with such knowledge, it is integral that researchers follow with a well-developed critique of the findings within the context of relevant scientific literature, together with a clearly articulated framework that evaluates the translational potential of the research within an applied context (Close et al., 2019; Waldman, 2006). Providing explicit evidence-led guidelines is an endeavor also highly encouraged to facilitate the translation of research, through highlighting how a study's findings can be implemented in real-world contexts to improve practice (Bishop, 2008). However, for practical advice to be optimised, it is useful to gain an in-depth appreciation of the practical challenges that key stakeholders encounter (Drust & Green, 2013; Harper et al., 2016c). Collecting survey data of this nature can promote a clearer understanding of the barriers preventing uptake of new knowledge, with such information being disseminated among the scientific community for researchers to address the practical issues that exist (Nosek et al., 2021). Another aspect of survey design that is fundamental to the progression of integrative sports science knowledge is retrieving practitioners' perceptions on future research ideas (Harper et al., 2016c; Hills et al., 2020). Direct revelations concerning practitioner recommendations for research are likely to inform research designs that possess higher ecological validity, in-turn, facilitating the adoption of research in the applied setting (Harper et al., 2016c; Hills et al., 2020). However, despite observations of mutual researcher and practitioner interest for engaging in research collaboration (Malone et al., 2019), there appears to be a large disconnect between the implementation of scientific innovation into the applied setting (Coutts, 2017).

Researchers are heavily criticised for failing to produce scientific studies that are appropriate for practitioners' use, with such findings often difficult to access and integrate within their practice (Bishop, 2008). Researchers are thought to focus on developing interesting (though not always useful) study ideas (Jones et al., 2019b), which are possibly generated through gaps identified in the evidence base (Bishop, 2008) or future research recommendations proposed by fellow academics. However, utilising survey research designs whilst strategically following an appropriate scientific model to initially interpret the 'real-world' context within which practitioners operate, may help overcome the current discordance between research-informed evidence and practice. An applied 'integration paradigm' model has been proposed, whereby, not only should research inform practice, but practice should also guide research (Haag, 1994). A more detailed and relevant framework pertaining to sports science has also been developed, termed the Applied Research Model for the Sport Sciences (Bishop, 2008). This eight-stage model provides a theoretical framework that guides the research process from ‘defining the problem’ (stage 1) to ‘implementation into a sporting setting’ (stage 8). The stages of the model involve the researcher applying their scientific knowledge and understanding of the sport and necessitates engagment with key stakeholders to identify and appreciate complex environmental challenges. Another research team have since revised the original model proposed by Bishop (2008) to promote an operational framework which is of direct relevance to conducting applied soccer science research (Drust & Green, 2013). The modifications to the newer model were largely focused around placing a greater emphasis on identifying the major barriers and practical challenges preventing research adoption to facilitate the completion of apposite and effective study designs (Drust & Green, 2013). Therefore, adhering to the conceptual principles of such an appropriate framework (Drust & Green, 2013) in order to assess the practices of applied practitioners, barriers reportedly impacting uptake and ideas for future research, will ultimately assist with translating research into optimal performance outcomes.

2.0 THE EXTRA-TIME PERIOD OF SOCCER: A SYSTEMATIC REVIEW

Publication arising from this chapter:

Field, A., Naughton, R. J., Haines, M., Lui, S., Corr, L. D., Russell, M., Page, R. M., Harper, L. D. (2020) The Demands of the Extra-Time Period of Soccer: A Systematic Review. Journal of Sport and Health Science, Doi: 10.1016/j.jshs.2020.03.008.

Author contributions

Adam Field wrote 90% of the first draft and Liam David Harper wrote 10% of the first draft of the manuscript. Adam Field and Liam David Corr carried out the screening process independently. All authors reviewed the manuscript at various stages throughout the editing process. All authors read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

2.0.1 ABSTRACT

Soccer match-play is typically contested over 90 min; however, in some cup and tournament scenarios, when matches are tied, they proceed to an additional 30 min, which is termed "extra-time". This systematic review sought to appraise the literature available on 120-min of soccer-specific exercise, with a view to identifying practical recommendations and future research opportunities. The review was conducted according to the PRISMA guidelines. Independent researchers performed a systematic search of PubMed, CINAHL and PsycINFO in May 2019, with the following keywords entered in various combinations: "soccer", "football", "extra-time", "extra time", "120 minutes", "120 min" "additional 30 minutes", and "additional 30 min." The search yielded an initial 73 articles. Following the screening process, 11 articles were accepted for analyses. Articles were subsequently organised into the following 5 categories: movement demands of ET, performance responses to ET, physiological and biomechanical responses during ET, nutritional interventions, and recovery and ET. The results highlighted that during competitive match-play, players cover 5%–12% less distance relative to match duration (i.e., $m \cdot min^{-1}$) during ET compared to the preceding 90 min. Reductions in technical performance (i.e., shot speed, number of passes and dribbles) were also observed during ET. Carbohydrate provision may attenuate reductions in dribbling performance during ET. Objective and subjective measures of recovery may be further compromised following ET when compared to 90 min. Additional investigations are warranted to further substantiate these findings and identify interventions to improve performance during ET.

2.1 INTRODUCTION

Soccer is a self-paced, irregular, multidirectional, and intermittent team sport typically contested over two 45-min halves and interspersed by a ~15 min HT rest interval. The more rigourous soccer investigations have shown that the physical response of players is progressively reduced across 90 min of match-play (Bradley et al., 2009; Lovell et al., 2013; Mohr et al., 2003; Weston et al., 2011a). The mechanisms for such responses are likely peripheral and central in origin (Mohr et al., 2003; Nédélec et al., 2013), although less is known about the fatigue profile of players during ET. When knockout-phase matches are tied during tournaments and an outright winner is required, an ET period of match-play commences 5 min after the 90-min match and consists of 15-min halves separated by a 2-min break during which teams typically swap ends of the pitch.

Extra-time was introduced as far back as 1897 in the English Football Association's rules of play and has been included in the FIFA set of rules for many years. Since this time, several different formats of ET have been trialled when there was a tie at the end of the 90-min match. Amid the chaos of war in the 1940s, new formats of ET were trialled when matches were tied at the end of the 90-min of normal time. For instance, matches that were level following 90 min of match-play during the Football League War Cup were decided according to the team that had the higher league position. Additionally, during the League South Cup in 1942–43, an alternative method was piloted: the first team to score or be awarded a corner after 20 min of ET won the match. However, following much controversy, this was soon reconsidered. Consequently, a "next goal wins" agreement was piloted during the 1946 Division Three North Cup. However, one match lasted 203 min, but the match remained tied and was thus "postponed". In 1993, the "golden goal" rule (first team to score in ET wins the game) and "silver goal" rule (the team leading at the end of the first 15-min period wins the match) were introduced by soccer's governing bodies. However, in late 2004 these alternative formats of ET were abolished, and the current regulations stipulate that a full 30-min ET period be played. If an outcome is not decided during this time frame, then a penalty shootout determines the winning team (Jordet & Elferink-Gemser, 2012; Lenten et al., 2013).

In recent years, ET has increasingly become a deciding factor in determining the outcome of cup competitions and tournaments. Since the 1986 FIFA World Cup competition, 33% of knockout matches have required ET. At the 2014 tournament, 50% of knockout matches required ET compared to 25% of matches at the 2002 and 2010 World Cup competitions, as well as 38% of matches at the 2006 World Cup tournament. More recently, 31% of knockout matches played at the 2018 FIFA World Cup proceeded to ET, with just one of the match outcomes decided during this period. Interestingly, for the first time in FIFA World Cup history, a team competed in three consecutive ET matches (round 1/16, quarter- and semi-finals) in the knockout phase of the competition (Kołodziejczyk et al., 2021). As a result, Croatia had competed for an additional 90 min on their route to the final versus counterparts France. Similarly, in the 2016 Union of European Football Associations (UEFA) championships, Portugal played ~60 min more match-time on their route to the final (which also proceeded to ET) than counterparts France. Therefore, the occurrence of an additional match duration associated with ET during major tournaments could lead to residual fatigue and underperformance, disadvantaging teams that have less recovery time versus their competitors.

When considering that the fatigue response associated with 90 min of soccer has been well documented (Mohr et al., 2005) and that fatigue-induced changes are sufficient to impair performance and injury-risk (Greig, 2008; Mohr et al., 2003; Small et al., 2010), the potential of additional physical loads being placed on players during ET could further result in reduced performance and an increased risk of injury. Epidemiological data appears to support this premise, with injury incidence shown to increase during the ET period of soccer (Aoki et al., 2012). Increasing knowledge in relation to the physical demands associated with ET periods may also be useful to ascertain whether there is a need to modify recovery strategies, manipulate nutritional intake and adapt training prescriptions for the purpose of reducing injury risk following ET and improving physical performance during this additional 30-min period. Evidence also suggests that fatigue has deleterious effects on aspects of technical performance (Russell & Kingsley, 2011), which has been shown previously to correlate with team success (Rampinini et al., 2009). Therefore, it may be desirable to determine the extent to which technical/skill actions are further affected by the additional exercise duration and potential fatigue imposed by ET. Furthermore, empirical evidence suggests that 67% of the soccer practitioners sampled (identified as working at professional clubs) agreed that ET was an important time period in determining tournament success (Harper et al., 2016d). Consequently, organising and appraising the ET literature is needed to analyse the scientific and empirical research findings that are currently pertinent for professional soccer practitioners' use in relation to ET. Additionally, identifying gaps in ET knowledge is warranted for the purpose of informing the content of the current thesis.

This review takes a systematic approach to organising the ET literature, which is warranted given that to date, and to the best of my knowledge, no review articles have been published on the ET period. Therefore, this systematic review aims to synthesise the literature associated with 120 min of soccer-specific activity, identifying the key themes of studies on this topic, characterising the methodologies employed, and informing researchers about the evolving knowledge of ET. The current review will also compare responses during the ET period to the preceding 90 min of match-play with the intention of informing practice. Lastly, gaps within the literature will be identified to guide the remainder of the work in this thesis.

2.2 METHODS

2.2.1 Search strategy: Databases, screening process and eligibility criteria

A review of the literature was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines. Keywords were entered in various combinations that related to the topic (“soccer” OR “football”) AND variations of terms for ET (“Extra-time” OR “Extra time” OR “Extratime” OR “120 minutes” OR “120 min”). During May 2019, the following databases were searched: PubMed (1950 – present), CINAHL (1981–present), and Psych Info (1806 – present). In addition, manual searches were conducted from the reference lists of the published manuscripts retained. Filters included original publications for which full English texts were available. Any potential articles were retrieved after the titles and abstracts were scanned. Once the screening of titles and abstracts was carried out and the removal of duplicates was completed, a systematic review strategy was employed to assess full texts. The inclusion criteria for these studies were as follows: (1) the study included relevant ET data, (2) participants were male soccer players ≥18 years old, (3) the ET period comprised a full 30-min duration, and (4) the study was written in English. Articles were excluded if they (1) used soccer-specific exercise <120 min in duration, (2) involved participants who had no previous soccer experience, (3) lacked an explicit description of their methodological processes, (4) took the form of a review article, (5) included female participants, or (6) could be classified as grey literature.

2.2.2 Data extraction

Two independent reviewers (AF and LDC) independently carried out the screening process. However, any disputes between the two reviewers regarding the inclusion of articles were discussed with and ultimately adjudicated by a third author (LDH). The two reviewers also extracted data from all articles, and, where appropriate, contacted the authors of the published articles for clarification on such data. Articles identified through other sources (e.g., known to authors), as well as those cited in the retained articles, were also considered for inclusion.

2.2.3 Assessment of methodological quality

As done previously by Sarmento et al. (2018b), the retained articles were each scored on a binary scale (0/1) used to assess quality in line with 16 individual quality criteria. These criteria were based on whether articles included: (1) a clear study purpose (2) a review of relevant literature (3) an appropriate study design for the research question (4) a detailed description of the sample (5) a justification of the sample size (6) informed consent (7 & 8) reliable and valid outcome measures (9) a detailed description of methods (10) statistically significant findings (11) an appropriate method of analysis (12) a justification for importance to practice, (13) a description of drop-outs (if any) (14) appropriate conclusions given the study design (15) implications for a given practice, and (16) the limitations of the research.

An option was provided for items 6 (“Was informed consent required?”) and 13 (“Were any drop-outs reported?”). If these criteria were “not applicable” to the article, then these two criteria were excluded as an option. For example, it must be considered that observational studies are not always required to obtain consent and will not necessarily have drop-outs to report. Therefore, this situation eliminates the negative impact that a 0 score may have on the article quality because it may not be applicable to the article. A percentage was calculated for each article as the summation of the quality score, divided by the relevant criteria included for the research design, thereby allowing comparisons among articles of different designs. Studies were characterised as having either low (≤50%), good (51%–75%), or excellent (>75%) methodological quality.

2.3 RESULTS

2.3.1 Study identification and selection

The initial database search returned 72 articles, and one article was located by the researchers during manual searches. These 73 articles were then exported to reference-managing software (Endnote X9, Clarivate Analytics, Philadelphia, United States) and duplicates were subsequently removed (n = 4). The titles and abstracts of each entry (69 articles) were then screened for relevance, which resulted in the rejection of 50 articles from the analysis. Following this trimming, the full texts of the remaining 19 articles were read diligently. Of the 19 articles, eight were excluded due to their irrelevance to the topic area. Following the full screening process, 11 articles were accepted for the systematic review (Figure 2.1).

2.3.2 Methodological quality

Quality scores are reported in Table 2.1; 10 studies were categorised as having excellent methodological quality, with one reported as good. A mean quality score of 88 ± 6% was established for the 11 articles. Although none of the articles attained a rating of 100%, the vast majority (10 of 11) achieved a considerably high score (>85%). None of the studies met criterion 13 (i.e., drop outs were not reported), although four studies were observational, so this criterion was not applicable. Minimal information pertaining to the justification of the sample size was given for six studies, and of the 11 articles analysed, three failed to address the study limitations (criterion 16).

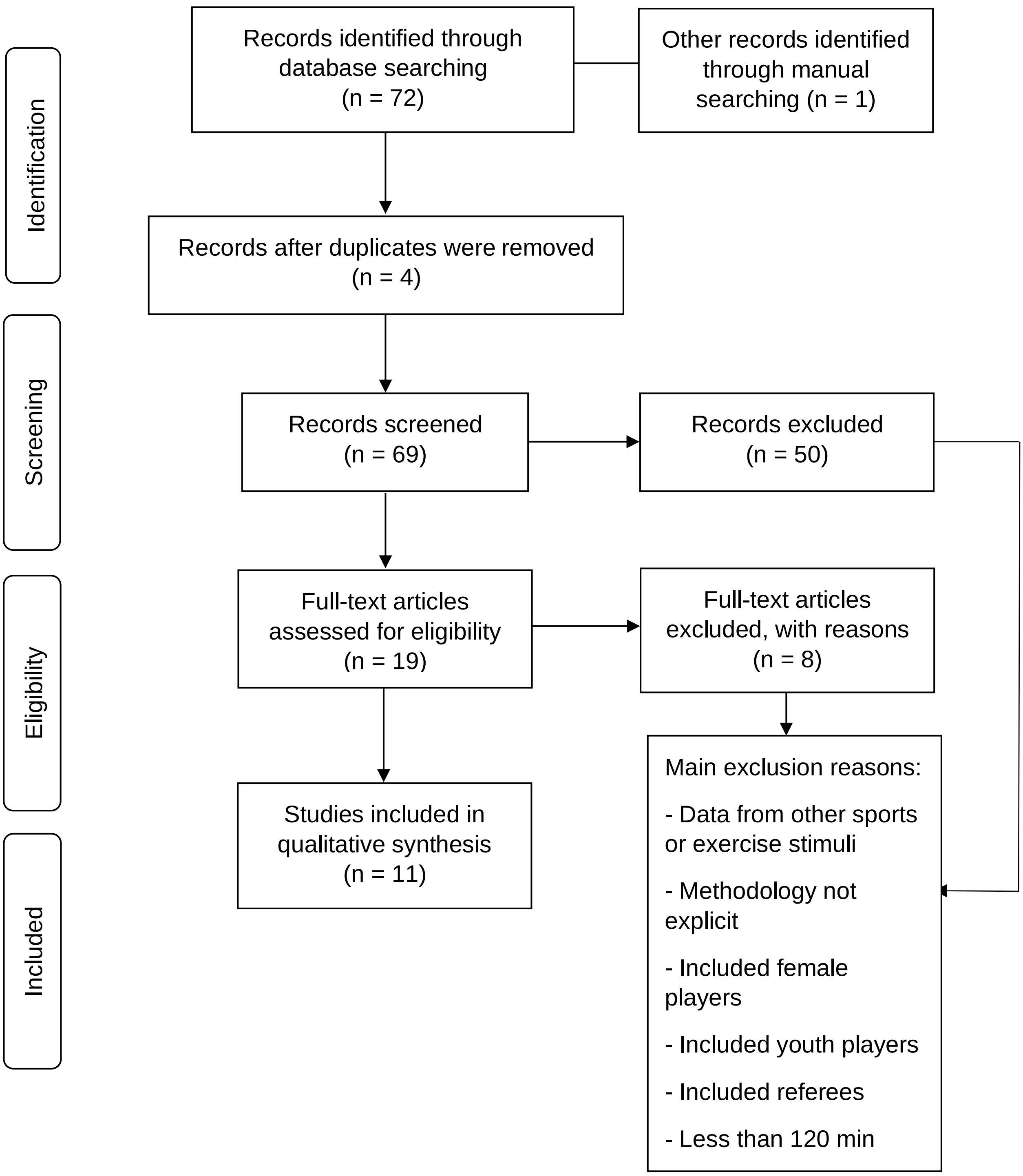

Figure 2.1. PRISMA flow diagram highlighting the study selection process for the present systematic review

Table 2.1. Quality assessment of the articles for the review adapted from Sarmento et al. (2018a)

Reference	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Score	%
Harper et al. (2016d)	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	15/16	93.8
Stevenson et al. (2017)	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	15/16	93.8
Harper et al. (2016c)	1	1	1	1	1	1	1	1	1	0	1	1	n/a	1	1	1	14/15	93.3
Harper et al. (2014)	1	1	1	1	0	1	1	1	1	1	1	1	n/a	1	1	1	14/15	93.3
Winder et al. (2018)	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	14/16	87.5
Russell et al. (2015b)	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	14/16	87.5
Harper et al. (2016b)	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	14/16	87.5
Harper et al. (2016a)	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	14/16	87.5
Goodall et al. (2017)	1	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1	14/16	87.5
Peñas et al. (2015)	1	1	1	1	0	n/a	1	1	1	1	1	1	n/a	1	0	1	12/14	85.7
Kubayi and Toriola (2018)	1	0	1	1	0	n/a	1	1	1	1	1	0	n/a	1	1	0	10/14	71.4

Notes: Low methodological quality (≤50%), good methodological quality (51% - 75%) and excellent methodological quality (>75%). n/a: not applicable

2.3.3 Study characteristics

A total of 296 individuals participated in the studies reviewed. The studies reported data on the following populations: professional (*n* = 160, 54.1%), professional academy (*n* = 16, 5.4%), semi-professional (*n* = 10, 3.4%), university-standard (*n* = 64, 21.6%) and practitioners (*n* = 46, 15.5%). The ages of participants (20 ± 3 years) were identified for the experimental research studies (*n* = 8), but age was not disclosed for the observational studies (*n* = 3). The majority of studies were quantitative (*n* = 10), with one study categorised as mixed methods (i.e., both quantitative and qualitative). A total of four of the investigations were conducted on match-play (36.4%), six studies utilised soccer-specific simulations (54.5%) and the findings of one article were based on practitioner perceptions of ET (9.1%). The 11 articles analysed in this systematic review were published since 2014.

2.3.4 Organisation of data

The studies incorporated within the review included relevant information pertaining to either (1) observations of professional matches that included ET, (2) a 120-min simulation (formatted as per a soccer match), or (3) the current practices of soccer practitioners with reference to ET. To classify the major topics of research associated with ET, one researcher categorised the papers, with debates resolved by discussion until a consensus of the entire research team was reached. Records were subsequently categorised into five main themes, with some articles containing data related to two or more themes. These themes were as follows: (a) movement demands of ET (3 articles), (b) performance responses during ET (8 articles), (c) physiological and biomechanical responses during ET (5 articles), (d) nutritional interventions (2 articles), and (e) recovery and ET (3 articles).

2.3.5 Movement demands of extra-time

As outlined in Table 2.2, three studies analysed the movements demands of ET using GPS and micromechanical electrical systems (MEMS) (Peñas et al., 2015; Russell et al., 2015b; Winder et al., 2018). Premier League players were observed using 10 Hz tracking devices. The players covered a distance of 14,106 ± 859 m over 120 min, with an additional 3213 ± 286 m covered during ET. In the same match, players performed 50 ± 18 sprints and covered 883 ± 400 m of high-speed distance across 120 min, with 12 ± 6 of those sprints and 153 ± 105 m of the high-speed distance being completed during the ET period. Furthermore, the study reported 946 ± 40 accelerations (>0.5 $m \cdot s^{-2}$) across 120 min, with 221 ± 14 accelerations during ET. A total of 908 ± 36 decelerations were observed over the course of the 120 min, with 207 ± 16 decelerations being completed during ET (Russell et al., 2015b). Winder et al. (2018) identified similar data (i.e., 15,400 ± 900 m of distance covered in 120 min of match-play) by four professional players competing in the third tier of English soccer. In addition, lower high-speed distance (791 ± 99 m) was observed across 120 min of match-play in the Winder et al. (2018) study. These players also completed fewer accelerations (358 ± 52) and decelerations (169 ± 38) over the course of 120 min. Peñas et al. (2015) analysed the physical performance data of 99 outfield players from seven matches that required ET during the FIFA World Cup held in Brazil in 2014. During the tournament, players covered an average total distance of 12,245 m across 120 min of match-play, with 2962 m covered during ET. Peñas et al. (2015) also reported 42 sprints during a 120-min match, with 9 sprints being completed during ET.

Table 2.2. Studies investigating movement demands of soccer during the ET period (mean ± SD)

Reference	Matches/ players	Data collection method	Variables measured	Key results
Russell et al. (2015b)	One reserve ET match/ English Premier League outfield players (*n* = 5).	10 Hz GPS units. Data collected across time points (E1, E2, E3, E4, E5, E6, E7, E8).	TD (m). Distance covered ($m \cdot min^{-1}$). HS distance covered (m). Total number of sprints, Total number of Acc (>0.5 $m \cdot s^{-2}$) and Dec (>0.5 $m \cdot s^{-2}$).	TD: 14,106 ± 859 m across 120 min; 3213 ± 286 m during ET. HS distance: 883 ± 400 m across 120 min; 153 ± 105 m during ET. Number of sprints: 50 ± 18 across 120 min; 12 ± 6 during ET. Number of Acc: 946 ± 40 across 120 min; 221 ± 14 during ET. Number of Dec: 908 ± 36 across 120 min; 207 ± 16 during ET.
Peñas et al. (2015)	Seven ET matches from 2014 FIFA World Cup / International outfield players (*n* = 99).	Official FIFA World Cup website: https://www.fifa.com/worldcup/archive/brazil2014/statistics/players/distance.html. Data collected across 1st half, 2nd half and ET.	TD ($m \cdot min^{-1}$), Distances covered at low, medium, and high speeds ($km \cdot h^{-1}$). Top speed ($km \cdot h^{-1}$) and avg number of sprints ($reps \cdot min^{-1}$).	TD: 12,245m across 120 min; 2962m during ET. Top sprint speeds: 24.06 ± 3.31 $km \cdot h^{-1}$ during ET. Avg number of sprints per min: 0.31 ± 0.14 $reps \cdot min^{-1}$ during ET.
Winder et al. (2018)	Three matches (two league and one cup) - only one ET match/English Championship outfield players (*n* = 4).	10 Hz GPS units. Data collected from MD1, MD2 (120 min) and MD3.	TD (m). HS distance covered (>18 $km \cdot h^{-1}$; $m \cdot min^{-1}$). Number of accelerations (>2 $m \cdot s^{-2}$) and decelerations (>2 $m \cdot s^{-2}$).	TD: 15,400 ± 900 m across 120 min. HS distance: 791 ± 99 m across 120 min. Number of Acc: 358 ± 52 across 120 min. Number of Dec:169 ± 38 across 120 min.

Note. Acc = acceleration, Dec = deceleration, ET = Extra-Time, GPS = global positioning system, HS = high-speed, E1 = 00:00–14:59 min, E2 = 15:00–29:59 min, E3 = 30:00–44:59 min, E4 = 45:00–59:59 min, E5 = 60:00–74:59 min, E6 = 75:00–89:59 min, E7 = 90:00–104:59 min, E8 = 105:00–119:59 min, MD1 = match day 1, MD2 = match day 2, MD3 = match day 3, TD = total distance, ↓ = decreased / lower than, ↑ = increased / higher than, ↔ = no difference.

2.3.6 Performance responses to extra-time

In the eight studies involving performance responses to ET, four analysed physical and technical performance variables during match-play (Harper et al., 2014; Kubayi & Toriola, 2018; Peñas et al., 2015; Russell et al., 2015b), whilst the remaining four assessed performance using free-running soccer simulations (Harper et al., 2016a; Harper et al., 2016b; Harper et al., 2016d; Stevenson et al., 2017) (Table 2.3). A 12% reduction in total distance covered during ET (107 m·min^{-1}) compared to 90-min (121 m·min^{-1}) of match-play was observed in reserve team Premier League players (Russell et al., 2015b). The same study examined a high-speed distance of 8 m·min^{-1} in 90 min and 5 m·min^{-1} during ET, indicating a 37.5% relative decrease in high-speed running activity. However, ~24% of the total number of sprints completed throughout the full 120 min of time (90 min of match-play + ET) were performed during ET. When comparing ET to the 90-min match duration, these players performed ~14% fewer accelerations and 12.5% fewer decelerations; both actions were defined as number of actions completed at >0.5 m·s^{-2} (Russell et al., 2015b). Similarly, movement data from 56 professional players during the 2016 UEFA European Championship (Kubayi & Toriola, 2018) revealed that a total distance of 113 ± 10 m·min^{-1} was covered during the first half, 107 ± 9 m·min^{-1} was covered during the second half and 98 ± 10 m·min^{-1} was covered during ET. Thus, 13% less relative distance was covered during ET than was covered in the first half.

Reductions in 30-m sprint velocity (~3%) and sprint maintenance (~4%) have been observed following 120-min versus post 90-min measures of simulated-soccer exercise in Premier League academy players (Harper et al., 2016b). Similarly, a decrease in 20-m sprint velocity following ET has been observed when compared to pre-first-half (~7%), post-first-half (~5%), pre-second-half (~2%), and post-second-half (~2%) in university-standard players (Stevenson et al., 2017). Another study observed reductions in 15-m sprint velocity during ET compared to measures taken during the first and second halves of simulated match-play in a separate investigation assessing professional academy players (Harper et al., 2016b). With reference to technical performance, Harper et al. (2014) found that the total number of successful dribbles was reduced and that the number of successful and total passes decreased by ~20% during the last 15 min of ET compared to corresponding measures of technical performance during the first half. Furthermore, utilising soccer-specific protocols to assess university-standard soccer players, reductions in both dribbling (Harper et al., 2016d) and shooting performance (Stevenson et al., 2017) have been observed during ET.

Table 2.3. Studies investigating performance responses during the ET period (mean ± SD)

Reference	**Matches/Protocol/ Players**	**Data collection method**	**Variables measures**	**Key results**
Harper et al. (2014)	18 matches. European soccer teams (specified as ranging from 1st to 3rd tier of their domestic leagues) and International teams. Number of outfield players per match (*n* = 15 ± 1).	Footage was obtained from televised recordings and soccer clubs. Data collected were manually coded by an experienced performance analyst. Data collected across time points (E1, E2, E3, E4, E5, E6, E7, E8).	Successful passes, unsuccessful passes, total passes, pass accuracy (%), successful dribbles, unsuccessful dribbles, total dribbles, dribble accuracy (%), shots on target, shots off target, total shots, shot accuracy (%), successful crosses, unsuccessful crosses, total crosses, cross accuracy (%), ball time in play (s).	Successful passes: ↓ E8 vs. E1, E2, E3, E4, E7. Total passes: ↓ E8 vs. E1, E3, E4, E7. Successful dribbles: ↓ E8 vs. E1, E3. Ball in play: ↓ E8 vs. E1. All other technical performance variables: ↔ were observed.
Peñas et al. (2015)	Seven ET matches from 2014 FIFA World Cup / International outfield players (n = 99).	Official FIFA 2014 World Cup website: https://www.fifa.com/worldcup/archive/brazil2014/statistics/players/distance.html. Data collected across three different match periods (1st half, 2nd half and ET).	TD ($m \cdot min^{-1}$). Distances covered at low, medium and high speeds ($km \cdot h^{-1}$). Time spent in low- (≤11.0 $km \cdot h^{-1}$), medium- (11·1-14.0 $km \cdot h^{-1}$) and HS (≥14.1 $km \cdot h^{-1}$) activities (%). Top sprint speed ($km \cdot h^{-1}$) and number of sprints ($reps \cdot min^{-1}$).	TD: ↓ during ET and 2nd half vs.1st half. Top sprint speeds: ↓ during ET vs. 2nd half and 1st half. Avg number of sprints per min: ↑ during 1st half vs. 2nd half and ET.
Russell et al. (2015b)	One reserve ET match/ English Premier League outfield players (n = 5).	10 Hz GPS units. Data collected across time points (E1, E2, E3, E4, E5, E6, E7, E8).	TD (m). Distance covered ($m \cdot min^{-1}$). HS distance covered (m). Total number of sprints, total number of accelerations and total number of decelerations (>0.5 $m \cdot s^{-2}$ >3.0 $m \cdot s^{-2}$).	TD: 121 $m \cdot min^{-1}$ across 90 min and 107 $m \cdot min^{-1}$ during ET (12% ↓). HS distance: 8 $m \cdot min^{-1}$ during 90 min and 5 $m \cdot min^{-1}$ across ET (37.5% ↓). Accelerations: 6 $m \cdot min^{-1}$ throughout 90 min and 7 $m \cdot min^{-1}$ during ET (~14% ↓). Decelerations: 8 $m \cdot min^{-1}$ during 90 min and 7 $m \cdot min^{-1}$ throughout ET (12.5% ↓).

Harper et al. (2016d)	120-min of soccer simulated match-play. University-standard outfield soccer players (n = 10).	No information available on data collection methods. Data collected across four time points: Post 1st half, pre 2nd half, FT, and post-ET.	CMJ height (cm), 20-m sprint (s) and 15-m sprint ($m \cdot s^{-2}$).	During final 15 min of ET: 15-m sprint speeds ↓ vs. all other time points. Following ET: 20-m sprint speeds ↓ vs. baseline and post 1st half. CMJ height ↓ vs. with baseline.
Harper et al. (2016b)	120 min of simulated soccer match-play / English Premier League academy soccer outfield players (n = 8).	15-m sprint velocities measured during 1st half, 2nd half and ET.	15-m sprint velocities ($m \cdot s^{-2}$).	Sprint velocities: ↓ by 6% during ET vs. 1st half.
Harper et al. (2016a)	120 min of a modified version of the soccer match simulation. English Premier League academy soccer outfield players (n = 8)	Video footage. (Data collected across time points (E1, E2, E3, E4, E5, E6, E7, E8).	30-m sprint velocities ($m \cdot s^{-2}$), 30-m repeated sprint maintenance (%), CMJ height (cm).	30-m sprint velocities: ↓. 30-m repeated sprint maintenance: ↓. CMJ height: ↓. (Comparisons are post-ET measures vs. post-90-min measures).
Stevenson et al. (2017)	120-min soccer match simulation. University-standard soccer players (n = 22).	Electronic Opto Jump system, timing gates and methods like that of Russell et al. (2012) were used to assess skill performance. Assessments were completed pre-1st-half, post-1st-half, pre-2nd-half, post-2nd-half and post-ET.	Peak 20-m sprint velocities ($m \cdot s^{-2}$), sprint decrement index (%), jump height (cm), shot speed ($m \cdot s^{-2}$), shot precision (cm), mean 15-m sprint velocities, ($m \cdot s^{-2}$), dribbling speed ($m \cdot s^{-2}$), dribbling precision (cm), dribbling success (%).	Jump height: ↓ following ET vs. pre-1st-half and post-2nd-half. Sprint performance: Relatively ↓ during ET vs. 75- to 90-min of simulated match-play. Shot speed: ↓ following ET vs pre-values (4.3%) and post-2nd-half (2.9%). Dribbling speed: ↓ during ET vs. 0 to 15-min of simulated match-play. Shooting performance: ↔ during ET.

Kubayi and Toriola (2018)	Four matches from 2016 European Championship, six teams / European players (n = 59).	InStat camera tracking system. Data collected across 120 min and categorised into 1st half, 2nd half and ET.	TD ($m \cdot min^{-1}$), walking ($m \cdot min^{-1}$) jogging ($m \cdot min^{-1}$), running ($m \cdot min^{-1}$), HS running ($m \cdot min^{-1}$), sprinting ($m \cdot min^{-1}$). Walking (0–7 $km \cdot h^{-1}$), jogging (7.1–14.5 $km \cdot h^{-1}$), running (14.6–20 $km \cdot h^{-1}$), HS running (20.1–25 $km \cdot h^{-1}$), and sprinting (>25 $km \cdot h^{-1}$).	TD: ↓ during 1st half vs. ET by 13%. TD covered by wide midfield players: ↓ by 17% during 1st half vs. ET. Sprinting performance ↓ during ET vs. 1st half. Greater ↓ were observed in attacking players vs. all other positions.

Note. CMJ = countermovement jump, ET = Extra-Time, FT = full time, FWC = FIFA World Cup, “HS” = high-speed, HS = high-speed, E1 = 00:00–14:59 min, E2 = 15:00–29:59 min, E3 = 30:00–44:59 min, E4 = 45:00–59:59 min, E5 = 60:00–74:59 min, E6 = 75:00–89:59 min, E7 = 90:00–104:59 min, E8 = 105:00–119:59 min, RSA = repeated sprint ability, SMS = soccer match simulation, TD = total distance, ↓ = decreased / lower than, ↑ = increased / higher than, ↔ = no difference.

2.3.7 Physiological and biomechanical responses during extra-time

A total of five studies (Goodall et al., 2017; Harper et al., 2016a; Harper et al., 2016d; Stevenson et al., 2017) investigated the physiological and biomechanical responses during ET using diverse equipment and methods (Table 2.4). Stevenson et al. (2017) observed increases in plasma glycerol, NEFA, interleukin-6 and epinephrine, as well as reductions in blood glucose and lactate concentrations during ET compared to 90 min of simulated match-play. Findings in studies of professional academy soccer players suggest that ET has an influence on markers of bicarbonate, base excess, haemoglobin, and blood pH. Significant reductions have also been observed in blood pH (0.01–0.03) levels during the final 15 min of ET versus baseline, HT, and the first 15 min of ET (Harper et al., 2016b). Furthermore, Goodall et al. (2017) observed that ET provoked an additional development of neuromuscular fatigue involving mainly the central nervous system, with significant perturbations in voluntary activation of the knee extensors and maximum voluntary quadriceps force produced at 120 min versus pre-match, HT and 90 min.

Table 2.4. Studies investigating physiological and biomechanical responses during the ET period (mean ± SD)

Reference	Matches/Protocol/ Players	Data collection method	Variables measured	Key results
Harper et al. (2016a)	120-min of a modified version of the soccer match simulation. English Premier League academy soccer outfield players (n = 8).	Fingertip capillary blood samples. HR monitor. Data collected across time points (E1, E2, E3, E4, E5, E6, E7, E8).	Blood glucose, lactate, and sodium ($mmol \cdot l^{-1}$).	Blood glucose concentrations: ↑ in CHO (5.6 ± 0.9) vs. PLA (4.6 ± 0.2) trials during E7. Blood lactate and sodium concentrations: ↔ were observed during ET vs. other time-points
Harper et al. (2016d)	120-min of soccer simulated match-play. University-standard outfield soccer players (n = 10).	Fingertip capillary and venous blood samples collected across time points (E1, E2, E3, E4, E5, E6, E7, E8).	CK ($\mu \cdot l^{-1}$). Insulin ($pmol \cdot l^{-1}$). NEFA ($mmol \cdot l^{-1}$). Glycerol ($mmol \cdot l^{-1}$). IL-6 ($pg \cdot ml^{-1}$). HR mean ($b \cdot min^{-1}$).	CK: ↑, NEFA: ↑, Glycerol: ↑, Insulin: ↔, IL-6: ↔ during ET vs. pre-exercise, post 1st half and pre 2nd half. HR mean: ↔ were observed during ET vs. other time-points.
Goodall et al. (2017)	120-min of soccer-simulated exercise. University-standard and semi-professional outfield soccer players (n = 10).	EMG activity was measured by Surface Ag/AgCl electrodes. HR data measured using HR monitors. Data collected pre-match, HT, FT and following ET.	ERT (N). MVC (%). $Q_{tw,pot}$ (%). VA (%). VA_{TMS} (%). RF M_{max} amplitude (mV). RF rms EMG M^{-1}. RF MEP/M_{max} area (%). VL M_{max} amplitude (mV). VL rms EMG M^{-1}. VL MEP/M_{max} area (%). MRFD ($N \cdot s^{-1}$). CT (ms). MRR (N/s). $RT_{0.5}$ (ms). HR ($b \cdot min^{-1}$).	MVC: ↓ throughout match-play, with ↑ decrements found in ET vs. HT and FT. $Q_{tw.pot}$ amplitude: ↔ were observed from HT to ET. VA: ↓ following ET vs. baseline. VA_{TMS}: ↓ during ET vs. baseline, although ↔ between ET, FT and HT. RF rms EMG M^{-1}: ↓ following ET vs. Baseline.
Harper et al. (2016b)	120-min of soccer match-play. Professional academy soccer players (n = 8).	Capillary blood samples (170µl) were taken at: Baseline, Pre-exercise pre, HT and at 15, 30, 45, 60, 75, 90, 105 and 120-min.	Blood calcium ($mmol \cdot l^{-1}$), potassium, ($mmol \cdot l^{-1}$), pH (AU), base excess ($mmol \cdot l^{-1}$), lactate ($mmol \cdot l^{-1}$), bicarbonate ($mmol \cdot l^{-1}$) and haemoglobin ($mg \cdot dl^{-1}$) concentrations.	Base excess: ↓ at 120-min vs. HT (-110 ± 159%), 2nd half and 105-min (-219 ± 280%). Bicarbonate: ↓ at 120-min vs. 105-min (23.7 ± 3.3%) and ↑ at 105-min vs. HT (22.2 ± 1.4%). Haemoglobin: ↑ at 120-min vs. baseline (6.8 ±5.6%) and pre-exercise (+7.9 ± 9%).

Stevenson et al. (2017)	120-min soccer match simulation. University- standard soccer players (*n* = 22).	Venous blood samples were collected at rest, pre-match, 15-min, 30-min, 45-min, HT, 60-min, 75-min, 90-min, 105-min and 120-min.	Lactate ($mmol \cdot l^{-1}$). Glycerol ($mmol \cdot l^{-1}$). NEFA ($mmol \cdot l^{-1}$). IL-6 ($pg \cdot ml^{-1}$). Adrenaline ($pmol \cdot l^{-1}$). HR peak ($b \cdot min^{-1}$). HR mean ($b \cdot min^{-1}$).	Blood lactate: ↓, Glycerol: ↑, NEFA: ↑, IL-6: ↑, Adrenaline: ↑, HR peak: ↑, HR mean: ↑ were observed during ET vs. 90-min.

Note. CHO = carbohydrate, CK = creatine kinase, CT = contraction time, EMG = electromyography, ET = Extra-Time, FT = full time, HR = heart rate, HT = half time, E1 = 00:00–14:59 min, E2 = 15:00–29:59 min, E3 = 30:00–44:59 min, E4 = 45:00–59:59 min, E5 = 60:00–74:59 min, E6 = 75:00–89:59 min, E7 = 90:00–104:59 min, E8 = 105:00–119:59 min , IL-6 = interleukin-6, MEP = motor evoked potential, Mmax = maximal M-wave, MRFD = maximum rate of force development, MRR = maximum rate of relaxation, NEFA = non-esterified fatty acids, PLA = placebo, RF = rectus femoris, rms = root-mean-squared, RT0.5 = half relaxation time, VL = vastus lateralis, ↓ = decreased / lower than, ↑ = increased / higher than, ↔ = no difference.

2.3.8 Nutritional interventions

A total of two articles (Harper et al., 2016a; Stevenson et al., 2017) investigated the efficacy of nutritional intervention during the ET period, and one empirical observation (Harper et al., 2016c) assessed the nutritional practices of soccer players in relation to ET through practitioner feedback. Harper et al. (2016a) observed that carbohydrate gels had no impact on physical performance; however, although the changes did not reach statistical significance, a 16% ± 17% increase in blood glucose and a 29% ± 20% improvement in dribbling precision during the final 15 min of ET was established. Stevenson et al. (2017) found that consumption of a low glycaemic index (GI) drink better maintained blood glucose concentrations by 13% compared to high GI in the second half of simulated match-play, particularly between 75- and 90-min, but the drinks had no effect during ET. Soccer practitioners specified that hydration and energy provision (e.g., high carbohydrate gels and drinks, high GI foods, caffeine, and protein) were prioritised in the intervals prior to and during ET (Harper et al., 2016c).

2.3.9 Recovery and extra-time

A total of three articles sought to determine the recovery responses following matches that required ET (Harper et al., 2016c; Russell et al., 2015b; Winder et al., 2018). Creatine kinase concentrations increased at 24 hr (236% ± 92%) and 48 hr (107% ± 89%) following ET compared to baseline in Premier League soccer players. Observations of CMJ height found reductions of 17.8% ± 11.2% at 24 hr and 7.4% ± 3.2% at 48 hr during ET in the same pool of players (Russell et al., 2015b). A case report found that ET impeded both subjective (wellness) and objective (CMJ height) measures of recovery 36 hr post-match compared to 36 hr following a 90-min match in the same weekly micro-cycle (Winder et al., 2018). Additionally, the findings from a mixed-method survey suggested that practitioners working in professional soccer believe that more research should be conducted on ET, particularly on fatigue responses (including recovery) and acute injury risk (Harper et al., 2016c).

2.4 DISCUSSION

The purpose of this systematic review was to collate, summarise and evaluate the current ET literature to determine the current practices being employed within soccer, highlight common research trends, and identify future research opportunities. Accordingly, studies included in the review were grouped for the purpose of assessing different aspects of ET. The main findings from this review are as follows: (a) players cover less total and sprint distances, relative to match duration (i.e., $m \cdot min^{-1}$), during ET compared to a 90 min match, (b) shot speed, number of passes and dribbles are also reduced during ET (c) consumption of carbohydrate gels may attenuate reductions in dribbling performance, and (d) matches that require ET may delay recovery further when compared to 90-min matches.

2.4.1 Movement demands of extra-time

The International Football Association Board (IFAB) has approved the use of GPS technologies during competitive matches, thus allowing a method of assessing the within-match running and movement indices of players. This is now commonplace in contemporary professional soccer and permits the measuring of variables such as distance covered, high-speed running distances, number of sprints and number of accelerations and decelerations (Ehrmann et al., 2016; Rossi et al., 2018). Russell et al. (2015b) were the first researchers to investigate the movement demands of soccer players during ET. This research influenced further investigations in which professional players were observed during a fixture-congested micro-cycle (i.e., 3 matches in 7 days) that incorporated an ET match (Winder et al., 2018). The disparities in high-speed distances are unsurprising in that the players analysed competed two tiers apart, and evidence suggests that high-speed performance is superior in high-level players during match-play (Mohr et al., 2003). Furthermore, the match requiring ET within the fixture-congested micro-cycle (Winder et al., 2018) was played against higher-calibre league opposition (differing by 47 league places at the time of the match), and contextual factors such as self-pacing strategies and match location may have influenced the performance of players (Paul et al., 2015). Furthermore, the four players used for the study played four discrete positions (two centre backs, one fullback and one central midfielder), and when expressed relative to playing time, there were considerable differences between individuals for the performance metrics (Winder et al., 2018). The data were not separated into periods of match-play (i.e., first half, second half, and ET) and therefore it was unable to be ascertained whether performance was affected during ET (Winder et al., 2018). Moreover, small sample sizes were used within both studies, making findings difficult to extrapolate, especially when differentiating findings across playing positions (Russell et al., 2015b; Winder et al., 2018).

In contrast, Peñas et al. (2015) investigated the movement demands of a substantial number of players (*n* = 99), thus addressing the limitation of using small samples utilised in both the aforementioned studies. The data from the seven matches analysed by Peñas et al. (2015) at the 2014 FIFA World Cup showed that positional differences existed (i.e., central midfielders cover more total and high-speed distance than other positions) for both 90-min matches and ET. However, irrespective of playing position, a decrease in movement during ET was evident, although it has yet to be elucidated whether this is attributable to physical fatigue or to a tactical approach. Therefore, investigating performance through simulated match-play may provide novel information on the mechanisms behind the reduced movement capacity.

2.4.2 Performance responses to extra-time

Match-to-match and between-player movement metrics are inherently variable in soccer. The literature suggests that match coefficient of variations (CVs) are between 26% (total distance) and 30% (high-speed running distance) (Fransson et al., 2018; Gregson et al., 2010; Rampinini et al., 2007) and player intraclass correlations are as sizeable as 32% and 39% for total and high-speed distance, respectively (Jones et al., 2019c). Therefore, match data must be interpreted with caution; hence the use of laboratory-controlled investigations. The first study to quantify changes in technical performance throughout 120 min of soccer was an empirical observation of 18 professional matches (Harper et al., 2014). The researchers observed a reduction in the total number of passes and successful dribbles, although they speculate that this may not be indicative of a reduction in technical proficiency *per se*. It is more likely that players lacked the physical capacity to be involved with build-up play, and thus, complete these technical actions. Therefore, the reduced technical performance is potentially related to the reduced physical capacity observed previously (Russell et al., 2015b; Winder et al., 2018). However, it is not clear whether this can be ascribed to increased fatigue or to player perceptions and subsequent pacing strategies. For example, anecdotal observations suggest that players may consciously reduce running output during ET and adopt a defensive approach in anticipation of a penalty shootout (Lenten et al., 2013). This may also explain the reason that matches are not often decided during ET. However, technical information about ET is scarce, and the precise mechanisms (i.e., physical and/or mental fatigue) modulating skill proficiency need investigating further. Given the possibility that the performance decrements are associated with temporal and cumulative fatigue, understanding the physiological and biomechanical mechanisms that influence performance during ET may have important implications during tournament and cup scenarios.

2.4.3 Physiological and biomechanical responses during extra-time

Goodall et al. (2017) observed that 120 min of simulated soccer elicited an additional development of central nervous system fatigue through reductions in maximal voluntary quadriceps force. It has previously been suggested that increases in peripheral biomarkers influence type III and IV nerve afferents, thus initiating temporary and cumulative reductions in central motor output (Amann et al., 2011; Amann et al., 2015; Gandevia, 2001). Reductions in central motor output could perhaps result in a player being at an increased risk of injury due to impaired muscular and cognitive functions (e.g., reactions, decision-making and perceptions) (Lorist et al., 2005; Miura et al., 2004). The observed increases in central fatigue during ET could theoretically explain the decrements in physical performance and increased likelihood of injury, particularly during match-congested schedules. However, there remains a paucity of research evaluating within-match changes in neural drive, and as such, measuring changes in surface EMG across 120-min of soccer-specific activity is an avenue requiring exploration.

It is unlikely that such trivial changes in pH (i.e., <0.2) observed by Harper et al. (2016b) can be associated with acidosis or result in the deleterious performance of 15-m sprints. This notion is supported by the lack of relationship observed between changes in sprint performance and blood pH in the same cohort. Investigations are required to determine whether the additional pressures of actual match-play (i.e., opposition players and environmental pressures) are likely to further exacerbate performance in comparison to simulated soccer matches. It is also apparent that studies in this section have adopted measures of RPE to assess subjective perceptions of fatigue (Goodall et al., 2017; Harper et al., 2016b; Harper et al., 2016d; Stevenson et al., 2017), although researchers have challenged that such a vague psychophysiological construct may be incapable of reflecting distinct perceptual sensations (Weston et al., 2015). Therefore, novel RPE methods termed d-RPE are sensitive measures of assessing perceptions of internal load (Barrett et al., 2018; Macpherson et al., 2019; McLaren et al., 2016; McLaren et al., 2020; Weston et al., 2015), and as such, should be employed to assess effort perceptions during ET investigations.

Throughout a 90 min period of match-play, soccer players reach 70% of their $\dot{V}O_{2max}$ (Bangsbo et al., 2007) and mean and peak heart rate values of 82% and 97%, respectively (Fransson et al., 2018; Owen et al., 2015). To fuel this exercise, glycogen is required during match-play, although evidence suggests that availability of intramuscular glycogen markedly decreases when exercise duration exceeds 90 min, after which fat stores are predominantly utilised (Watt et al., 2002). The data on ET suggest a temporal change occurs in the primary energy pathway utilisation as a match progresses throughout 90 min and into ET (i.e., the pathway switches to predominately fat oxidation) (Stevenson et al., 2017). This could be due to elevated adrenaline and diminished insulin concentrations. Increased levels of adrenaline stimulate muscle glycogenolysis via activation of phosphorylase α (Watt et al., 2001) and dampened insulin concentrations promote lipolysis because it inhibits the activation of protein kinase A and Akt (Choi et al., 2010). As fatty acid metabolism is not the optimal energy pathway required for high-speed exercise, this could plausibly explain the transient impairments in physical performance observed during ET. However, before interpreting these data, it is prudent to highlight the fact that substrate utilisation has merely been estimated during ET using venous blood sampling techniques. Therefore, alternative measurements should be taken during simulated match-play that are used as surrogates for substrate utilisation through measures of gaseous exchange (i.e., RER).

Adrenaline concentrations increase markedly during ET (Stevenson et al., 2017), and as such, it could be hypothesised that muscle glycogen decreases further during this additional 30-min period. However, to date, no study has measured muscle glycogen in response to 120 min of soccer match-play (simulated or otherwise). Krustrup et al. (2006) took muscle biopsies from players during a 90-min soccer match and observed significant reductions in glycogen concentrations at 90 min compared to pre-match. These concentrations were at critically low levels for some players, and any further decrease, such as during a potential ET period, could negatively impact performance and recovery. During 120 min of cycling, Logan-Sprenger et al. (2013) observed significant reductions in muscle glycogen from 80 min to 120 min. These reductions were concomitant with increases in fat oxidation, circulating NEFA and adrenaline concentrations. Although the findings were derived from a cycling-exercise stimulus, these data support previous ET findings (Stevenson et al., 2017). Additional work is needed to verify whether reductions in muscle glycogen are uniform with both the blood glucose and cycling data above, and whether nutritional intervention, such as carbohydrate intake, can attenuate reductions when matches proceed to ET.

2.4.4 Nutritional interventions

Acute carbohydrate provision is currently utilised in soccer to mitigate performance decrements (Russell et al., 2012). The improved skill performance following carbohydrate consumption has been associated with an increased supply of cerebral glucose (increasing oxidative metabolism) and protection against central nervous system fatigue (Querido & Sheel, 2007; Russell et al., 2012). Although somewhat extraneous and not specific to soccer, empirical evidence suggests that the provision of carbohydrate over 120 min of cycling exercise can ameliorate reductions in performance (Jentjens et al., 2005). This mechanism may partly explain the reason that carbohydrate–electrolyte gel ingestion and raised blood glucose improved dribbling precision during the latter 15 min of ET (Harper et al., 2016a). However, contrastingly, a separate investigation suggests that consuming a carbohydrate solution does not impact blood glucose concentrations during ET, nor attenuates reductions in physical or skill indices (Goodall et al., 2017). Currently, there is a dearth of scientific literature that has investigated nutritional intervention for soccer players during ET even though in an online questionnaire, soccer practitioners ranked nutritional interventions as the most important area for future research in relation to ET (Harper et al., 2016c). Of the few articles that exist, the contrasting interpretations make it difficult to delineate whether carbohydrate consumption has positive effects on performance during ET. However, practitioners recommend that carbohydrate and protein intake should be increased immediately following ET and maintained up to 48 hr following an ET match in the belief that such consumption accelerates recovery (Harper et al., 2016c). Further empirical investigation appears warranted to explore practitioners' use and periodisation of nutrition to enhance recovery.

2.4.5 Recovery following extra-time

The impact of 120 min of soccer match-play on the recovery process has received little attention in the literature. Practitioner surveys show that 67% of those completing the survey do not alter preparatory strategies prior to a match that might require ET, although 89% do adjust recovery modalities following a 120-min match (Harper et al., 2016c). This seems appropriate considering that the small body of literature suggests that reductions in high-speed distance, as well as dribbling and passing accuracy are evident during a 90-min match that was played 64 hr after an ET match in the same weekly micro-cycle (Winder et al., 2018). Therefore, more robust investigations, employing rigourous methods that elicit control over confounding variables, are needed with larger sample sizes and using reliable soccer-specific protocols to assess various recovery measures. Increased understanding of changes in recovery following ET and the efficacy of commonly used recovery methods could better inform soccer practitioners of which practices might be optimal following ET. Future research of an empirical nature should also be carried out to comprehensively assess the applied practices of soccer practitioners around recovery and the ET period of soccer.

2.4.6 Methodological limitations

It is acknowledged that confounding factors, methodological inconsistencies within the literature (e.g., competitive level of players and high-speed thresholds), and measurement errors (e.g., GPS devices and HR monitors) are limitations of the review. However, given the limited number of ET studies, all applicable studies were included in the review. However, the quality appraisal classified 10 of the 11 studies as excellent, thus, the studies were high in experimental rigour. However, blinding of assessors and outcome measures was not considered in the quality appraisal tool as it was not feasible. Another potential flaw is the exclusion of female players. However, comparisons between sexes are difficult given the physiological differences (Minahan et al., 2015), and the fact that the only published ET research that includes females involves a shorter duration of match-play (i.e., two 10-min periods) (Williams et al., 2019). Finally, searching for merely English publications may have eliminated other potentially relevant manuscripts written in another language.

2.5 CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

Little research has been conducted on soccer matches that require the additional period of ET. Investigations using 120-min soccer simulations and actual match-play have observed decreases in physical, technical, and physiological parameters, as well as compromised recovery of jump indices and subjective wellness. The lower intensities of play identified during ET could partly be due to the change in the predominant substrate pathway (aerobic glycolysis to fat oxidation) used for energy production. However, further investigations are necessary since biomechanical fatigue may cause these reductions in running performance, altering the predominant fuel source. However, the inherent between-match variability and pacing strategies evident in soccer match-play leaves the inferences open to contextual factors. Thus, the need to use bouts of standardised running profiles under controlled conditions to evaluate the fatigue and recovery responses of soccer players is justified. These studies should be undertaken with the intention of reducing fatigue-related injuries across successive matches during fixture-congested periods that involve ET scenarios.

Competitive match-play may yield ecologically valid performance responses; however, it is likely that individual profiles during a soccer match vary given the influence of situational variables and between-match and inter-individual variations. This premise also applies to the disparate activity profiles of each playing position. Although there is a plethora of literature documenting the demands of match-play across various playing positions over 90 min (Barros et al., 2007; Bloomfield et al., 2007; Dalen et al., 2016), there is currently a lack of position-specific information during ET periods. Most soccer simulations are based on an average profile and fail to account for positional differences. Furthermore, the use of soccer-specific protocols allows the comparison of individual changes to baseline scores. Therefore, when translating sprint performance during match-play, it is important to consider the individual speed of players, since slower players may not attain the thresholds at their given maximal sprinting speed. Reduced sprint speeds observed during soccer protocols could perhaps be linked to the reduced physical capacity (i.e., high-speed running) because players are not able to reach and sustain these speeds. Therefore, through the longitudinal monitoring of players, researchers should endeavour to quantify external load characteristics according to playing positions during tournaments and cup competitions. By doing so, it may be possible to collate an adequate grouping of data that provides a comprehensive assessment of the influence of ET on the discrete demands of each playing position.

Research on soccer has typically focused on 90 min of match-play, but this research may lack applicability to ET in many different bespoke populations and areas of the sport. For example, there is a notable absence of research on female soccer players and their performance during

ET. Likewise, research on cognitive performance during ET is an area in which additional research is needed. Additional investigations into the extent to which ET influences the physical and technical performance parameters and recovery both for male and female soccer players is also warranted. Since competitive tournaments are often held in hot climates, the impact of playing ET in high ambient temperatures (e.g., >30°C) should be investigated since a player's performance, recovery and overall health may be negatively affected by playing ET in hot weather. Similarly, research on the effect of playing ET at high altitudes is needed, particularly since the FIFA World Cup in 2026 may be played in stadiums located in cities at elevations ≥1500 m (e.g., Mexico City's Estadio Azteca at 2915 m, Guadalajara's Estadio Akron at 1566 m, and Denver's Mile High Stadium at 1610 m).

It should be noted that ET occurs relatively infrequently compared to typical 90-min matches, although it is recommended that coaches and practitioners prepare for this possibility in tournament scenarios. Carefully orchestrated fuelling strategies are advocated during the days leading up to matches that may require ET, and carbohydrate should be provided on match day (including 5 min prior to ET). This may require additional effort so that individual player preferences are readily available in the 5-min break prior to ET, thus increasing player compliance. Administering nutrition that has ergogenic properties and elicits faster absorption rates, such as caffeine gum, may be efficacious prior to ET (Ranchordas et al., 2018). Additionally, the highly taxing and intermittent nature of soccer reduces endogenous glycogen (Krustrup et al., 2006), so it is recommended that practitioners adopt nutritional strategies that replenish intramuscular and liver glycogen stores following ET matches.

Players susceptible to fatigue can be identified through use of several contemporary methods, including tracking data, biochemical and hydration assessments and sleep and wellness profiles. These data may assist in making informed decisions about a player’s readiness and when a player should return to training following ET matches. The time-course for a player’s recovery may be delayed after an ET match compared with a typical 90-min match. However, if reductions in training load and intensities are warranted to aid recovery between matches, sport science practitioners and coaches should collaborate to ensure that players maintain optimal fitness. It may also be beneficial to adopt training programmes in the period prior to competition so that players are prepared for matches that have the potential to progress to ET. Although it may be difficult to discern precisely when such training programmes should be implemented during fixture-congested tournaments, it is crucial to do so to reduce injury risk whilst optimising player performance.

2.6 THESIS PURPOSE AND AIMS

The review of the literature was undertaken to emphasise the key areas of research that necessitate research focus with reference to ET. The key focus outlined for warranting future research consideration are specific biomechanical and physiological assessments during ET, and investigations into recovery practices and responses following ET through use of empirical and controlled experimental research.

This thesis focuses on several distinct aspects of biomechanical and physiological fatigue, and recovery responses related to ET and 120 min of soccer-specific exercise. All studies will employ a discrete methodological approach to data collection, although similarities exist between the experimental studies and all chapters are united by one common theme — the ET period of soccer. The original contribution to knowledge will relate to the controlled experimental research that takes a novel approach to assessing biomechanical and physiological aspects during simulated ET scenarios, and evaluates recovery following 120 min of soccer-specific activity. Another key contribution to knowledge is based on novel evidence pertaining to recovery practices employed in relation to ET in real-world environments. This is appropriate since there is a scarcity of empirical observation relating to the challenges faced in an applied environment and a potential lack of knowledge, which could perhaps negatively impact practice. Therefore, acquiring a more complete depiction of some of the limitations associated with working in an applied setting and the way in which soccer practitioners operate and overcome these issues with reference to ET and recovery will be a novel finding. The systematic review in this chapter was designed to highlight gaps in research with apposite research ideas being identified which will ultimately inform the main body of the thesis. Translating evidence-led research back into an applied setting effectively to increase uptake remains a key challenge. However, since practitioner feedback will be sought, it is the intention of the final experimental chapter carried out in this thesis that the transfer of ‘science to practice’ is maximised for assessing recovery.

The few experimental and observational research articles that are available are largely lacking in experimental control over the activity profile and primarily employ designs that use match-play models to investigate ET. Research investigating the biomechanical responses to ET is scarce. Furthermore, although there are studies that have been conducted to analyse the physiological changes during ET, there are various aspects associated with physiology and metabolism during the ET period that remain to be investigated. The few articles documenting the recovery profile post ET are indicative of detrimental recovery implications for players. However, none of the ET literature examining aspects of recovery are comprehensive, nor employ research that controls for confounding factors. Considering the limitations within the literature and the information from this section, the overarching objective of this thesis is to determine whether the additional 30 min period of ET further impacts biomechanical and physiological indices of fatigue, and recovery. The thesis has five main aims, which are systematically and explicitly addressed in five individual chapters:

(1) The aim of **Chapter 2** is to systematically review and appraise the current ET literature with the intention of identifying potential gaps and methodological concerns to assist with guiding the direction and developing ideas to inform future investigations such as the ones conducted throughout this thesis.

(2) Prior to moving forward with investigating the biomechanical performance and recovery responses, it is the intention of **Chapter 4** to assess the test-retest reliability of a validated soccer-specific treadmill-based protocol to allow for reliable responses to be obtained and more robust conclusions to be formed as a result of such data. The secondary aim of the research is to examine the biomechanical and physiological responses to 120 min of soccer-specific exercise; yielding novel ET data.

(3) Considering the lack of research into various biomechanical indices during ET period, the main aim of **Chapter 5** is to investigate the EMG, peak torque and PlayerLoad™ responses to 120-min of soccer-specific exercise.

(4) The aims of **Chapter 6** are to explore practitioners' perspectives and ascertain pertinent information regarding (i) the applied practices and approaches currently employed in relation to recovery and ET, and (ii) obtain recommendations for new lines of research in relation to ET and recovery. This information will be used to both acquire apposite future research ideas which will inform Chapter 7 and provide practical advice for practitioners responsible for managing recovery modalities for players exposed to ET matches.

(5) The practitioners surveyed in Chapter 6, identified 'tracking physical and physiological responses' following ET matches as the most important future research area. Therefore, the impact that 90 and 120 min has on the recovery response will be investigated in **Chapter 7** using the reliable soccer-specific exercise protocol. The study will aim to directly compare recovery in the same cohort of players undertaking both trial durations to assess whether ET has a negative impact on recovery versus 90 min of intermittent soccer-specific activity.

Taken collectively, the findings of this thesis are intended to provide novel information, potential application, highlight pertinent research avenues moving forward and contribute new insights into the biomechanical and physiological responses to 120 min of soccer-specific activity, and recovery following the ET period.

3.0 GENERAL METHODS

3.0.1 OVERVIEW

The methods reported in this chapter are those that describe many of the methodological procedures employed within the current thesis. The description of methods unique to the individual studies are not incorporated within this section but can be found in the methods sections of the specific chapters.

3.1 PARTICIPANTS AND RECRUITMENT

University-standard and semi-professional soccer players were used for Chapters 4, 5 and 7 (herein referred to collectively as experimental chapters). For the experimental chapters, male participants were approached, either via email, social media (e.g., Twitter), face-to-face interactions around the university campus, or personnel previously known to the research team. For recruitment of practitioners working within professional, international, academy or semi-professional soccer; social media and email were utilised, or practitioners known to the research team were contacted and asked to complete the online surveys (Chapter 6). Eligibility to partake in the research was determined by clearly defined inclusion and exclusion criteria which are highlighted in each chapter.

3.2 ETHICAL CONSIDERATIONS

Each study was accepted by the University of Huddersfield, School of Human and Health Sciences, School Research Ethics and Integrity Committee (see Appendix 1 for an example of institutional ethical approval) and conformed with the Declaration of Helsinki. During recruitment, potential participants were provided with written and verbal information of study procedures and were also informed of the inherent risks involved (See Appendix 2 for an example participant information sheet). Prior to data collection, both oral and written informed consent were obtained from participants (See Appendix 3 for an example of a consent form). It was expressed that participants had the right to withdraw at any point during the study without explanation or ramifications. However, participants were informed that once their data were analysed, then withdrawal would no longer be possible. To maintain anonymity, participants were assigned an identification number and all data were stored on a password protected computer in keeping with the General Data Protection Regulation (GDPR) guidelines for no longer than necessary prior to being permanently deleted. To minimise potential risk to participants, all apparatus were calibrated as per the manufacturers guidelines and thoroughly risk assessed prior to the commencement of testing procedures (see Appendix 4 for an example risk assessment).

3.3 PRE-EXERCISE MEASURES

All procedures in this section are applicable to the experimental chapters. Upon arrival at the laboratory on testing day, participants first supplied written informed consent and filled out a health screening questionnaire to highlight potential risks and contraindications to exercise. A mid-flow urine sample was completed, and osmolality was assessed (Osmocheck, Vitech Scientific, West Sussex, UK). Previous research has reported the reliability for urine osmolality via the Osmocheck (CV 9.6%; TE 0.19) (Sparks & Close, 2013). A capillary blood sample was then extracted to assess resting BLa concentrations (see section 3.8.3 for description). The participants' mass (SECA 875 electronic flat scale, SECA, Germany) and stature (SECA 213 portable stadiometer, SECA, Germany) were determined in conformity with the International Standards for Anthropometric Assessment. Participants were asked to wear minimal clothing for the mass assessment. Free-standing stature was recorded once participants were stood with feet placed parallel and touching, the calcanei positioned against the back of the height instrument whilst adopting an upright posture. The head was positioned in the Frankfurt plane and the measurement was taken when the height gauge was lowered to the vertex of the cranium.

3.4 PRELIMINARY TESTING AND FAMILIARISATION

An assessment of $\dot{V}O_{2max}$ was completed using a graded ramp test in the experimental chapters. The maximal test was completed until volitional exhaustion and in line with recommended criteria for valid $\dot{V}O_{2max}$ attainment (Beltz et al., 2016). Volitional exhaustion was defined as the point at which the participant expressed that they could no longer continue exercising due to exhaustion. Since previous research has demonstrated that athletes attain their highest $\dot{V}O_{2max}$ at eight min (Yoon et al., 2007), the current incremental exercise protocol was designed to capture the plateau as close to this duration as possible. The incremental test began at 10 km h^{-1}, increasing by 1 km h^{-1} every 30 s, until 17 km h^{-1} was reached. Once the participants reached a velocity of 17 km h^{-1}, a gradient of 0.5% was applied at each 30 s interval until volitional exhaustion was achieved (refer to section 3.8.1 for further details). Approximately a week prior to the experimental trials, participants also completed a 120 min familiarisation of the soccer-specific exercise. The same visit was also used to fully habituate participants with all techniques involved with experimentation procedures to ensure that any observed effects were not due to participant unfamiliarity, thus, minimising potential learning effects (Hopker et al., 2009). Participants were also familiarised with the treadmill-based warm-up and stretching sequence during the first visit that was to be later completed prior to all experimental trials.

3.5 WARM-UP PROCEDURES

Prior to commencement of all experimental trials, participants performed a cardiovascular-based warm-up on the treadmill. The treadmill-based warm-up included several *ad hoc* speed changes and was developed to elicit an increased physical response associated with a pre-match warm-up procedure (Greig et al., 2006). The participants then completed a standardised sequence of stretching techniques at the preliminary visit (stretches outlined below). Stretches were dynamic in nature and progressive from slow to fast stretches as this has previously shown to increase heart rate, core temperature as well as elicit activation of the nervous system (Fletcher, 2010). The stretches were also designed to mimic the movements performed by players during competitive match-play (Mann & Jones, 1999). Each of the seven stretches were maintained for 45 s (~5 min in total) and were performed immediately after the treadmill warm-up.

Stretching sequence:

- Alternate dynamic forward lunge with rotation
- Alternate dynamic lateral lunge
- Alternate reverse lunge with a reach
- Squat with single leg lift
- Alternate single-leg deadlift
- Alternate hip rotations
- Alternate leg bounds

3.6 EXPERIMENTAL CONTROL AND RESTRICTIONS

If a specific blood marker was measured in several chapters, the analytical methods used have been described below. However, for markers exclusive to each chapter a description of the analytical procedures involved can be found in the relevant methods section. The same applies to specific exercise and dietary restrictions.

Participants were asked to avoid strenuous exercise external to the study for 48 hr before testing and for the entirety of data collection. The consumption of alcohol, non-steroidal anti-inflammatory drugs (e.g., ibuprofen) and foods rich in polyphenols were prohibited for 72 hr prior to the trial until the end of the experimental period. These restrictions were imposed to ensure that physical activity and dietary intake did not confound the results collected from each study. Verbal confirmation was sought to confirm that participants conformed with these measures. If numerous trials were completed, then participants were asked to wear similar clothing and the same running shoes for each trial which were undertaken at the same time of day to minimise circadian variation (Duglan & Lamia, 2019).

The consumption of standardised quantities of water intake was permitted at pre-determined time intervals in Chapter 4 (further details are available in this section). This ensured that between-trial conditions were standardised, and RER data were not influenced by carbohydrate intake. For chapters 5 and 7, a carbohydrate electrolyte beverage and (or) water was consumed *ad libitum*. For Chapter 4 and 7, fluid intake was recorded by the research team and replicated for the subsequent trial. No other source of nutrition was ingested throughout the experimental trials.

For Chapter 4, participants were asked to track and duplicate dietary consumption between the main trials beginning 24 hr before until the end of testing. In Chapter 7, participants were asked to record their dietary intake from the 24-hr period prior to the first trial up until the end of the data collection period (i.e., 72 hr post trial). Participants were then asked to replicate their dietary intake as close as possible throughout the second trial. Chapter 7 contains further details. Compliance was assessed in Chapter 7 using weighed food diaries (see Appendix 5 for an example of a weighed food diary) for the five testing days (24 pre- to 72 hr post-trial). A 'snap and send' method was utilised to approximate portion sizes and food wastage. This procedure involved images of participant nutrition (acutely before and after consumption) being sent to the lead researcher via a free smartphone messaging application (WhatsApp). This method has been shown to be a valid and reliable procedure for estimating dietary intake and food wastage (Costello et al., 2017; Zhang et al., 2015a). The food diaries were input into dietary analysis software (Nutrimen.co.uk, Dark Green Media Ltd ©2016). This was to check that nutritional composition was similar between trials and, as such, did not largely impact upon the study outcome measures.

3.7 MOTORISED TREADMILL

The soccer-specific exercise was completed using a motorised treadmill (h/p/cosmos pulsar® 3p: h/p/cosmos sports & medical GmBH, Nussdorf, Germany). The manufacturers software (H/P/Comsos Para Graphics, H/P/Comsos Sports and Medical GmbH, Germany) was downloaded onto a personal computer which was used to directly control the treadmill activity. The treadmill possessed a gradient range of 0—25%, a velocity range of 0—11.1 $m{\cdot}s^{-1}$ and the treadmill belt surface was 1.90 m in length and 0.65 m in width.

3.8 WITHIN TRIAL MEASURES

3.8.1 Respiratory measures

For Chapter 4, respiratory flow volumes were measured continuously throughout exercise. Initial procedures involved the Metamax® 3B-R2 system being turned on 20 min prior to use and calibrated as per manufacturer guidelines. The gas analyser was first calibrated with certificated gas mixtures of known concentrations (oxygen [O_2]: 16%, carbon dioxide [CO_2]: 4%, nitrogen [N_2]: 80%) and subsequently authenticated against ambient air (Macfarlane & Wong, 2012). The flow sensors were calibrated for volume with a Hans Rudolph 3-L turbine calibration syringe (5530 series, Hans Rudolph, Shawnee, Kansas, USA). A silicone rubber facemask (Hans Rudolph 7450 series V2™, Han Rudolph Inc., Shawnee, Kansas, USA) was applied over the mouth and nose, secured by an adjustable headpiece and strap clips. This was fixed to a bidirectional volume transducer (Triple® V, Cortex, Germany), which provided breath-by-breath air flow data through an automated portable gas analysis system (Metamax® 3B-R2, Cortex, Leipzig, Germany). The sample line was attached to the bidirectional digital turbine rate to determine the concentration of O_2 expired (using an electrochemical cell) and CO_2 produced (using an infrared analyser). Prior to the experimental trials, information was manually input into the manufacturer software (Metasoft®Studio Cortex software, version 3.7.0 SR2, Germany) including participant anthropometric measures, size of the face mask, relative humidity, and environmental temperature. The computer installed software, telemetrically received breath-by-breath data measured by the portable system. Upon completion of the exercise trial, raw data files were exported to a Microsoft excel file. Mean ($\dot{V}O_{2mean}$) and peak ($\dot{V}O_{2peak}$) oxygen consumption, as well as RER values were calculated across fixed bouts of exercise. The RER measures the proportion of O_2 consumed and CO_2 produced (Jeukendrup & Wallis, 2005) and is computed automatically using a standard metabolic algorithm (Wasserman et al., 1987). The same portable system was used across both trials as the Metamax® 3B-R2 has previously shown to have ideal intra-device Intra-Class Correlation Coefficients (ICC) of 1.0 and technical error of measurement of 0.8–1.7% for $\dot{V}O_2$ and $\dot{V}CO_2$ (Macfarlane & Wong, 2012).

3.8.2 Accelerometry

For experimental chapters, participants wore a trunk-mounted GPS-unit (OptimEye S5, Catapult Sports, Scoresby, Australia) which was placed directly inferior to the 7th cervical vertebrae inside the pouch of a tightly fitted branded garment to reduce excessive movement. Housed within this device are internal micro-sensors which continuously recorded data throughout the soccer-specific exercise. The integrated micro-sensors include 100-Hz accelerometery (Kionix KXPA4, Kionix Inc., Ithaca, NY, USA) which quantifies linear motion and accelerations, tri-axial 100-Hz gyroscopes adopted for the measurement of angular motion and rotation, and 100-Hz triaxial magnetometers for measuring the orientation and direction of an object. Data derived from each of these sensors quantifies a software-derived parameter termed PlayerLoad™ (Catapult Sports, Australia), which is a vector magnitude calculated as the square root of the instantaneous rate of change in acceleration across individual planes of motion and divided by a scaling factor (Graham et al., 2020). During activity involving multi-planar movements, the tri-axial accelerometer, gyroscope and magnetometers are needed for data amalgamation from individual planar contributions to enumerate PlayerLoad™ (Douglas et al., 2019; Van Iterson et al., 2017).

Tri-axial data were recorded across the vertical (PL_{V}), anterior-posterior ($PL_{A\text{-}P}$) and medial-lateral ($PL_{M\text{-}L}$) vectors. The summation of the planar contributions provided a combined value (PL_{Total}) and were expressed as arbitrary units. The percentage contributions for vertical ($PL_{V\%}$), anterior-posterior ($PL_{A\text{-}P\%}$) and medial-lateral ($PL_{M\text{-}L\%}$) were also computed automically by Catapult Open Field software (OpenField 1.17.0 Catapult Sports, Melbourne, Australia). Data were post-processed and defined across pre-determined bouts of exercise. The same device was used between trials as Catapult OptimEye S5 intra-device test-retest has demonstrated good reliability as evidenced by low CVs (0.01% - 3.0%) and ICCs (0.77 - 1.0) (Nicolella et al., 2018).

3.8.3 Blood lactate concentrations

In the experimental chapters, capillary finger prick blood samples were taken once the foremost droplet of blood was discarded and stored in 20 ml tubes (containing heparin to preclude blood coagulation). The following precautions were taken during sample collection to avoid possible inaccuracies arising: an adequate quantity of blood was taken; caution was applied to reduce alcohol contamination and the microvette was handled in such a way as to prevent air pockets entering. Once calibrated through use of manufacturer calibration fluid, the Biosen C-Line (EKF-diagnostic GmBH, Cardiff, Wales) was used to measure BLa concentrations using an enzymatic amperometry method. Previous manufacturer pilot testing demonstrated CVs of 1.5% for the determination of BLa.

3.8.4 Differential ratings of perceived exertion

For experimental chapters, exercise intensity was assessed via d-RPE using the Borg 15-point (6 ‘no exertion’ — 20 ‘maximal exertion’; see Appendix 6) linear scale with verbal expressions used to label some of the integers in-between (Borg, 1998). The scale remained present and visible during the testing procedures. Participants were asked to differentiate using lower-limb muscle (RPE-L), cardiorespiratory (RPE-B) and overall (RPE-O) ratings of exertion. Ratings were taken in a counterbalanced order to eradicate the potential influence of order effects (McEwan et al., 2018). Scores were taken across exercise at each 15-min mark as a representation of the accumulated exertion for the previous bout of exercise. Investigating d-RPE is a novel method that has shown to possess moderate-to-high within-player and between-match typical error of 7.9–12.4% and 8.8–13.7%, respectively (Weston et al., 2015). The following recommended researcher guidelines and instructions for collecting effort perceptions were adapted and used to ensure validity and reliability of collecting subjective interpretations of perceived exertion (Pageaux, 2016):

1) Written instructions were provided to the participants before each testing session including, the Oxford English Dictionary definition of effort "*the physical or mental energy that you need to do something; something that takes a lot of energy*". Participants were also provided with the opportunity to ask questions.
2) Attempts were made to assist participants in rating effort independently from other exercise-related sensations (i.e., pain, discomfort, and force).
3) Written and verbal descriptions of each of the individual d-RPE constructs were provided for the participants as below:
   - Lower-limb muscle effort: "how hard did you perceive the exercise to be based solely on leg exertion?"
   - Cardiorespiratory effort: "how hard did you perceive the exercise to be based solely on breathing and cardiovascular exertion?"
   - Overall effort: "how hard did you perceive the exercise to be based on your overall exertion?"
4) Participants were asked to read the scale to familiarise with the verbal anchors and how each subjective descriptor corresponded to the numerical integers on the rating scale. Participants then practiced providing the corresponding number for the verbal descriptor that best represented their perceived effort.
5) Reference points were provided against which participants could rate their perception of effort. For a maximal exertional reference point on the 15-point Borg scale, participants were asked to provide ratings that would represent effort perception at the latter few seconds of the $\dot{V}O_{2max}$ test performed. The participants were also informed that HR could be used as a reference point for which scale ratings could be provided (e.g., 60 bpm [6 on the scale] could represent a resting value and 200 bpm [20 on the scale] could correspond to maximal effort).
6) An explanation was provided that the perception of effort must reflect the cumulative exercise performed up to that point and not resemble the preceding 15-min block. The participants were also instructed that the effort ratings should not refer to the feelings experienced during the latter stages of exercise, but instead the entirety of the 15-min bout of exercise.
7) A full habituation was conducted across the 120 min familiarisation session, which involved eight measures per participant to ensure reliability and validity of the d-RPE

assessment. During the familiarisation trial, the participant provided the reasons for their effort perception ratings and the lead researcher reiterated some of the considerations previously mentioned to maximise measurement consistency.

3.9 RECOVERY MEASURES

3.9.1 Biochemical measures

3.9.1.1 Determination of blood creatine kinase, creatinine, urea and aspartate aminotransferase concentrations

Whole blood was collected in Chapter 7, through use of a finger prick blood capillary sampling technique. Upon disposal of the first droplet, approximately 200 μl of blood was drained into heparinised tubes (Microvette® 300 LH, Sarstedt, Nümbrecht, Germany) and stored in a laboratory refrigerator at ~4°C. Precisely 32 μl of blood was pipetted onto a test strip and analysed for CK, creatinine, urea and AST concentrations using a colorimetric assay procedure (Reflotron® plus, Roch Diagnostics, Switzerland). The Reflotron® plus was calibrated before use, through use of the manufacturer provided magnetic testing strips. As reported by the manufacturer, inter-assay variations are 3.5% and intra-assay reliability for this method has previously demonstrated CV's of <3% (Howatson & Milak, 2009). A single researcher analysed all samples to minimise as much as possible the influence of inter-assay variation.

3.9.2 Muscle function testing

3.9.2.1 Countermovement jump

In Chapter 4 and 7, CMJ was assessed using a portable optical measurement system (Opto Jump, Microgate, Italy). Test-retest of the Opto Jump system has demonstrated excellent reliability with ICC's of 0.98 and low CV's of 2.7% previously observed (Glatthorn et al., 2011). Participants were asked to stand with feet placed shoulder width apart, and upon instruction, promptly descend into a ~60° squat position and immediately jump vertically with maximum effort. Participants were asked to maintain hand to hip contact to negate the influence of arm swing on jump height and land in the same position as take-off. Three maximal efforts were performed with a 30 s rest period separating each attempt; the mean of the three jumps were presented for analyses as per previous research (Clifford et al., 2016a). A 30 s static duration was used to enable full recovery between jumps as determined during pilot testing.

3.9.2.2 Reactive strength index

An Identical portable optical measurement system was used to the one described in section 3.9.2.1. Participants were instructed to mount and drop from a 0.3 cm platform, and instantly upon landing, transition into a vertical jump with maximal effort whilst increasing flight time and minimising ground contact time. This specific strategy previously elicited the greatest RSI values (Young & Behm, 2003). The RSI values were subsequently calculated automically via manufacturer software using the sum of jump height (cm) divided by ground contact time (ms) (Opto Jump, Microgate, Italy). As seen in section 3.9.2.1, participants were instructed to keep their hands on their hips and the number of efforts and rest periods were also identical to this section. Previous test-retest reliability measures revealed that ICC's for this method were >0.9 (i.e., excellent) (Flanagan et al., 2008).

3.9.2.3 Isokinetic dynamometry peak torque

A unilateral peak torque isokinetic assessment of the conKE and eccKF was undertaken in Chapter 5 and 7 using a Cybex HUMAC Norm isokinetic dynamometer with HUMAC2009 software version 0.8.4 (CSMI, USA). Neither verbal nor visual feedback were provided to participants during the experimental testing period. The dynamometer was calibrated and setup according to manufacturer recommendations. Ideal individual participant seating positions were documented during familarisation and repeated across subsequent tests. Whilst in a seated position, constraints were applied across the thigh, positioned marginally above the knee, as well as across the pelvis and shoulders to reduce excessive movement. The femoral epicondyle of the knee was aligned with the rotation centre of the crank, the cuff on the padded lever arm was placed 5 cm proximal to the malleoli, and the ipsilateral limb was restrained via a padded support. Before isokinetic measures were taken, the tested limb remained passive and was weighed at anatomical zero (full knee extension), which was considered alongside torque values to correct the effects of gravity. The limb weight contribution is automically applied during each rep as the limb torque (mass) multiplied by the sine(angle). The above set up was conducted with adherence to the manufacturer instructions manual.

The dominant leg (identified as the preferred kicking leg) was tested through a range of 0−90° (0° representing full extension and 90° full flexion). The angle of eccKF peak torque has previously been captured at a 32—47° at 60 deg·s^{-1}, and between 46—51° at 300 deg·s^{-1} for measures taken prior to, immediately post and 48 hr following a simulated soccer match in semi-professional players (Page & Greig, 2020). Measures were taken across a range of angular velocities including 180, 270 and 60 deg·s^{-1} (3.14, 4.71 and 1.05 rad·s^{-1}). This order was purposely chosen to preclude the fatiguing influence of slower isokinetic speeds (Greig, 2008). For each speed, participants performed one set of five consecutive repetitions with a passive 30 s rest period separating each set as per previously published works testing eccentric knee flexor and (or) concentric extensor peak torque in soccer players (Greig, 2008; Page et al., 2019; Rhodes et al., 2019). Previous researchers have reported ICCs of 0.95 to 0.97 for conKE and eccKF torque measures (de Carvalho Froufe Andrade et al., 2013).

3.10 STATISTICAL ANALYSES

Several statistical approaches are employed for each study and as such, specific methods are described in each of the relevant chapters.

4.0 TEST-RETEST RELIABILITY OF THE BIOMECHANICAL PERFORMANCE AND PHYSIOLOGICAL RESPONSES TO 120 MINUTES OF SOCCER-SPECIFIC EXERCISE

Publication arising from this chapter:

Field, A., Corr, L. D., Haines, M., Lui, S., Naughton, R. J., Page, R. M., & Harper, L. D. (2020) Biomechanical and Physiological Responses to 120 min of Soccer-Specific Exercise. Research Quarterly for Exercise and Sport, 91(4) 1-13.

Author contributions

Adam Field wrote the first draft of the manuscript, and collected and analysed all data. All authors reviewed the manuscript at various stages throughout the editing process. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

4.0.1 ABSTRACT

The main purpose of the study was to assess the test-retest reliability of the responses to a 120-min treadmill-based soccer-specific exercise protocol. The secondary aim of the research was to investigate the biomechanical and physiological responses to soccer-specific exercise incorporating an ET. Twelve soccer players performed 120 min of treadmill-based soccer-specific exercise twice within 7 days to assess test-retest reliability. Measures of absolute (typical error [TE] and coefficient of variation [CV]) and relative (Pearson's correlation coefficient [*r*]) reliability were used to determine the consistency between the test results obtained in the first and second testing sessions. Tri-axial (PL_{Total}) and uni-axial PlayerLoad™ in the vertical (PL_{V}), anterior–posterior ($PL_{A–P}$), and medial–lateral ($PL_{M–L}$) planes were monitored using a portable accelerometer. The respiratory exchange ratio (RER) was also recorded throughout exercise. At the end of each 15-min period, players provided d-RPE for legs (RPE-L), breathlessness (RPE-B) and overall (RPE-O), and capillary samples were taken to measure BLa concentrations. All measures were compared across 15 min blocks of standardised activity. CVs were <10% and *r* demonstrated moderate-to-very strong (0.33–0.99) reliability for all PlayerLoad™ variables, RPE-B, BLa, and RER. A main effect for time was identified for PL_{Total} (p = .045), PL_{V} (p = .002), $PL_{A–P}$ (p = .011), RER (p = .001), RPE-L (p = .001), RPE-O (p = .003), and CMJ (p = .020). A significant increase in PL_{Total} was observed during 105–120 min (234 ± 34 a.u) versus 0–15 min (215 ± 25 a.u, p = .002, d = 0.6), 15–30 min (216 ± 23 a.u, p = .008, d = 0.6), 30–45 min (220 ± 22 a.u, p = .017, d = 0.5), 45–60 min (226 ± 27 a.u, p = .019, d = 0.3), 60–75 min (226 ± 24 a.u, p = .028, d = 0.3), and 75–90 min (229 ± 25 a.u, p = .017, d = 0.2). A decrease in RER was evident during 105–120 min (0.87 ± 0.03 a.u) versus 0–15 min (0.92 ± 0.02 a.u, p = .001, d = 2), 15–30 min (0.92 ± 0.02 a.u, p = .009, d = 2), 30–45 min (0.91 ± 0.02 a.u, p = .007, d = 1.6), 45–60 min (0.89 ± 0.02 a.u, p = .012, d = 0.8), 60–75 min (0.90 ± 0.02 a.u, p = .031, d = 1.2), and 75–90 min (0.89 ± 0.02 a.u, p = .001, d = 0.8). This study suggests that the current treadmill-based soccer-specific exercise protocol is a reliable tool for assessing biomechanical and physiological variables across 120 min. The results also suggest that biomechanical efficiency is compromised, and an increased rate of lipolysis is observed during ET. These data have implications for practitioners interested in fatigue-induced changes during ET.

4.1 INTRODUCTION

The demands of soccer match-play have evolved over recent years with contemporary data suggesting an increased ball speed (Wallace & Norton, 2014), along with greater high-speed distances covered during elite soccer matches (Bush et al., 2015). Soccer matches are high in ecological validity in such a way that they possess a realism that is difficult to replicate in an unnaturalistic setting. However, performance metrics vary considerably from match-to-match (Gregson et al., 2010) and logistical constraints limit physiological measurements during competitive games (Coutts et al., 2007). Therefore, simulating soccer match-play has been proposed as a feasible alternative to guarding against injury-risk by negating the physical contact associated with match-play (Page et al., 2015), which is responsible for ~70% of injuries (Aoki et al., 2012). Simulating match-play also enables researchers to determine the extent to which their study is adequately powered (Abt et al., 2020), whilst also manipulating certain variables to evaluate their impact on performance (Currell & Jeukendrup, 2008). However, aside from being valid and sensitive, it is important that the exercise simulation possesses good reliability (e.g., the extent to which reproducible exercise demands and responses are elicited) to enable meaningful inferences to be drawn from the simulation data (Currell & Jeukendrup, 2008; Harper et al., 2016d; Russell et al., 2010). Reliability refers to the agreement between repeated measurements, including instrument error, within-examiner error of measurement and within-subject (e.g., player values) variability (Drust et al., 2007).

Components of match-play are typically simulated using free running and field-based protocols as they have the capacity to incorporate skill actions, while replicating the multi-directional nature of soccer-specific activity (Greig & Siegler, 2009; Small et al., 2010). However, such protocols are hindered in their ability to regulate an individual's activity profile and prevent self-pacing, while also failing to simulate the mechanistic demands associated with soccer match-play (Page et al., 2015, 2019). Motorised treadmill simulations excel as they preclude player pacing approaches due to the standardised bouts of activity that can be implemented (Page et al., 2015); thus, alterations in running technique, efficiency and gait are likely as a result of fatigue. Therefore, employing fixed periods of activity enables researchers to assess whether the reduced running output (distances and speed) observed towards the latter end of each half of matches (Weston et al., 2011b) is due to a reduced physical capacity and a compromised state preventing maintenance of running or a fatigue-induced subconscious effort to minimise injury-risk.

A motorised treadmill-based soccer-specific exercise protocol (Page et al., 2015) has shown to be valid when assessing the physiological and biomechanical responses across successive bouts of soccer-specific activity (Page et al., 2016; Page et al., 2019). The simulations' activity profile integrates standardised bouts of intermittent activity designed to preclude the self-pacing element associated with soccer match-play (Page et al., 2015). However, although the protocol has been validated and the biomechanical and physiological responses have been evaluated over a 90 min duration, the reliability of such responses have yet to be assessed. The distances covered (15.4 ± 0.9 km) (Winder et al., 2018) and number of sprints actions (n = 50 ± 18) (Russell et al., 2015b) observed during the simulation (16.26 km distance and 56 sprints) are also consistent with 120 min of actual-match play. Matches can proceed to ET in the knockout phase of certain major tournaments and cup competitions, when matches are tied, and an outright winner is required. However, to date, the Soccer Match Simulation (Russell & Kingsley, 2011) is the only reliable soccer-exercise stimulus over 120 min (Harper et al., 2016d). Although this free-running simulation has merit, there is an absence of ET treadmill-based protocols that have been deemed reliable, and thus, there is scope to further investigate the reliability of the biomechanical and physiological responses over 120 min.

Changes in PlayerLoad™ have been observed during the latter stages of a contemporary 90-min soccer simulation, indicating a reduced movement efficiency (Page et al., 2015), but whether these fatigue-induced deteriorations are exacerbated during ET has yet to be investigated. The aetiology of such changes may be a decreased neuromuscular control (Oliver et al., 2014), potentially compromising dynamic joint stability (Hughes & Watkins, 2008). This could be owing to a reduced absorption capacity and increased stress response to soft tissues (Hughes & Watkins, 2008), leading to impaired movement efficiency which suggests an increased load per distance covered (Barrett et al., 2016) and a potential increased injury-risk. Therefore, investigating changes in PlayerLoad™ responses over 120 min may help elucidate whether recovery and injury-risk are impacted further by the additional duration and running output associated with ET. Whilst PlayerLoad™ is a useful measure of external load, internal load (e.g., HR and RPE) can provide important information pertaining to the impact of external stressors (Macpherson et al., 2019). Although increases in RPE have been observed during ET (Harper et al., 2016d), d-RPE responses have yet to be collected during this period. Therefore, as this measure is applied, sensitive and easily administered (Macpherson et al., 2019), investigating d-RPE responses may assist in capturing multiple dimensions of exertion to facilitate understanding of players' perceptions of load over 120 min of soccer-specific exercise.

Higher plasma glycerol, NEFA and adrenaline as well as lower BLa and glucose has been observed during ET, which is indicative of an increased rate of lipolysis (Stevenson et al., 2017). However, previous researchers have used venous blood samples to estimate these changes in substrate utilisation over 120 min (Stevenson et al., 2017), which is logistically difficult to measure during exercise. An alternative measure used to estimate relative proportions of carbohydrate and fat oxidation is RER. To date, researchers have yet to employ treadmill-based soccer simulations for ET and have thus far failed to calculate RER over 120 min. Therefore, using RER to estimate substrate utilisation may provide practitioners and coaches with novel insight into carbohydrate usage during ET and whether dietary intake must be modulated to spare endogenous carbohydrate use and help maintain performance.

The systematic review in Chapter 2 revealed that there is a paucity of research investigating certain biomechanical and physiological measures, such as the ones described above. Additionally, to carry out these assessments in a controlled environment, a reliable 120-min treadmill-based soccer-specific exercise protocol was required. Therefore, the main aim of this study was to examine the test-retest reliability of the biomechanical and physiological responses to 120 min of treadmill-based soccer-specific exercise. A secondary aim was to investigate the biomechanical and physiological responses to 120 min of treadmill-based soccer-specific exercise. It was hypothesised that the reliability of the responses would demonstrate good reliability. Hypotheses of the secondary aim included: 1) increases in PlayerLoad™ would be indicative of a reduced efficiency during ET 2) a shift in RER towards the predominant use of fat oxidation would be observed during ET 3) d-RPE would increase as a function of exercise duration.

4.2 METHODS

4.2.1 Participants

University-standard (n = 6) and semi-professional (n = 6) outfield soccer players (age: 21.3 ± 2.9 years, stature: 178.5 ± 7.1 cm, mass: 70.42 ± 8.47 kg, $\dot{V}O_{2max}$: 57 ± 7 ml·kg·min^{-1}, max HR: 199 ± 3 b·min^{-1}) with ≥ 2 years of soccer experience were recruited for participation. An *a priori* power analysis (G*Power©, version 3.1.9.2, 2017, Germany), deemed a sufficient sample size of 11 based on ≥80% power (1 – β), an alpha (α) of 0.05 and a large effect size (d = 0.8) based on previous PL_{Total} data (Page et al., 2019). Exclusion criteria specified the diagnosis of lower-limb musculoskeletal injury within the preceding six months, any medical condition affecting participation following completion of a medical screening questionnaire and a $\dot{V}O_{2max}$ ≤ 48.5 ml·kg^{-1}·min^{-1}, consistent with previous ET literature (Stevenson et al., 2017). Furthermore, participants were asked to refrain from strenuous exercise 48 hr prior to testing. Institutional ethical approval was granted to allow the undertaking of research and written informed consent was obtained from participants prior to data collection.

4.2.2 Preliminary visit and familiarisation trials

Participants attended the laboratory on four separate occasions. The preliminary visit (1st visit) was used to measure body mass and stature (see section 3.3 for specific details). A graded ramp test was also completed to assess $\dot{V}O_{2max}$ (see section 3.4 for specific details). A 72-hour period then separated the 1st visit from the familiarisation trial (2nd visit). This visit involved a full habituation of all experimental procedures including the full 120 min of soccer-specific exercise, and the completion of a standardised, treadmill-based warm-up (see section 3.4 for specific details). Thereafter, main trial 1 (3rd visit) was performed, followed by main trial two (4th visit). The familiarisation and both main trials were interspersed by seven days to ensure full recovery. Identical procedures were followed for main trials one and two to assess the reliability of the biomechanical and physiological responses and all other data are presented from main trial 2.

4.2.3 Main trial procedures

Participants were asked to record and replicate dietary intake for both main trials commencing 24 hr prior until completion of exercise. Both main trials were conducted at the same time of day to minimise the effects of circadian variation. Upon arrival at the laboratory, a mid-flow urine sample was provided to measure urine osmolality (Osmocheck, Vitech Scientific, West Sussex, UK). A blood sample was then taken at rest followed by an assessment of body mass and stature. The warm-up was completed, and 200 ml of water consumed. CMJ measures were taken after the warm-up, followed by a 5 min passive rest period. The quantity of water administered was standardised and provided at HT (500 ml), full-time (300 ml) and during the two min interval (200 ml) separating ET as per previous investigations (Harper et al., 2016d). Assessments of CMJ and body mass were taken upon completion, immediately followed by an assessment of urine osmolality to determine hydration status; euhydration was accepted as <600 $mOsm \cdot kg^{-1}$ (Hillman et al., 2013). Urine-corrected mass changes were calculated for body mass assessment.

4.2.4 Soccer simulation

A modified version of a treadmill-based soccer-specific exercise protocol 90 min in duration (Page et al., 2015) was performed on a motorised treadmill (h/p/ cosmos pulsar® 3p: h/p/cosmos sports & medical GmBH, Nussdorf, Germany). It comprised two 45 min halves interspersed by a 15 min passive recovery HT break, followed by a 5 min passive rest period, and a further two 15 min periods (ET), separated by 2 min passive recovery. Similar to previous research (Harper et al., 2016d), the soccer-specific exercise was performed in 15 min blocks (with data assessed likewise). The changes in speed were set at the treadmill limit (1.39 $m \cdot s^{-2}$) and players reached maximal speeds of 25 $km \cdot h^{-1}$ throughout the protocol (Figure

4.1). This soccer-specific exercise was designed to simulate the durations, intensities and the velocity profile of match-play based on previous notational analyses (Mohr et al., 2003). The participants covered a distance of 16.26 km (similar to actual match-play) (Winder et al., 2018) during the soccer-specific exercise with blood capillary samples, and d-RPE provided at the end of each 15 min bout of activity. Mean values for RER, $\dot{V}O_2$, HR, and PlayerLoad™ data were taken as an average across each 15 min block of exercise. Data were divided into the following epochs: E1 (00:00–14:59 min), E2 (15:00-29:59 min), E3 (30:00-44:59 min), E4 (45:00-59:59 min), E5 (60:00-74:59 min), E6 (75:00-89:59 min), E7 (90:00-104:59 min) and E8 (105:00-119:59 min).

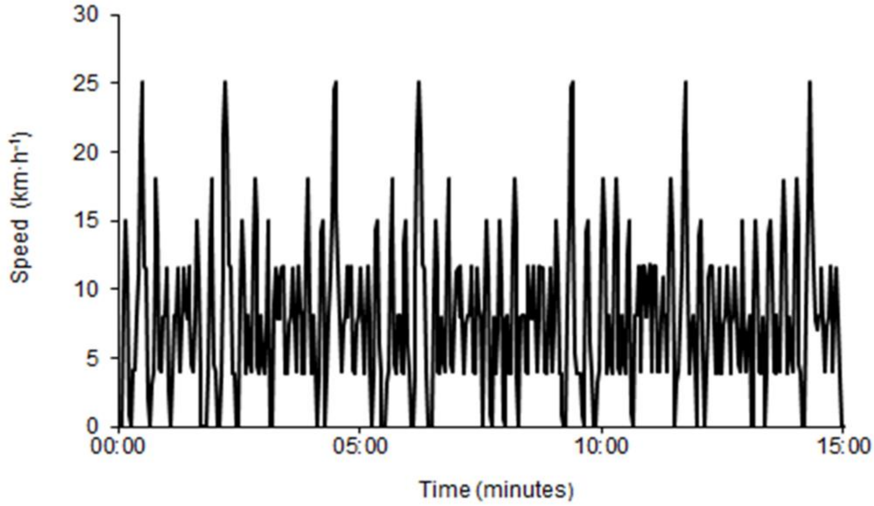

Figure 4.1. A schematic of an individual 15-min bout of the soccer-specific exercise

4.2.5 Experimental measures

Respiratory flow volumes were recorded continuously throughout the trial. Thereafter, individual $\dot{V}O_{2mean}$ values were expressed as the average O_2 intake across each 15 min bout and the highest value reached was defined as $\dot{V}O_{2peak}$. Additionally, the RER was calculated and defined as the mean over each 15 min bout of the trial (see section 3.8.1 for specific details).

The treadmill automatically paused at the end of each 15 min block of exercise, a finger-tip blood capillary sample was then taken, with the protocol subsequently manually resumed. The samples were analysed after the trial for BLa (Biosen C-Line; EKF-diagnostic GmBH, Cardiff, Wales). In addition, d-RPE was provided through use of the Borg 15-point (6-20) linear scale (Borg, 1998) and participants were asked to differentiate between RPE-L, RPE-B and RPE-O for each 15 min block of activity. To eliminate order effects, these values were collected in a counterbalanced order. CMJ height was measured using two portable photoelectric cells (Optojump, Italy) and was calculated using Opto Jump software. The jumps were separated by a 10 s passive rest interval for each of five respective time-points (rest, post HT, pre-second-half, 90 min and 120 min). Participants were instructed to jump with hands on hips to nullify the influence of momentum; the mean of three jumps were presented for analyses.

All PlayerLoad™ data were defined across each 15 min period of soccer-specific exercise (see section 3.8.2 for specific details). Participants were assigned the same unit for each trial to avoid inter-unit variation, as the Catapult OptimEye S5 device has been shown to possess high intra-unit reliability, yet inconsistent inter-unit reliability (Nicolella et al., 2018). A HR sensor (Polar H10, Polar USA, United States) was synchronised with the GPS unit, attached directly to the vest via a snap fastener and worn inferior to the sternum to quantify both mean (HR_{mean}) and max (HR_{max}) HR values; HR_{max} was defined as the peak value recorded during a given 15 min exercise bout.

4.2.6 Statistical analyses

Data were analysed using Statistical Package for the Social Sciences (IBM SPSS Statistics 24 for windows, SPSS Inc., Chicago, IL, USA). Statistical significance was set at $p \leq .05$ prior to analyses. All data were expressed as mean ± standard deviation (SD), unless indicated otherwise. In accordance with Hopkins (2000), test-retest reliability was established using typical error (TE) and CV for absolute reliability, and Pearson's correlation coefficient (*r*) for relative reliability. For CV, <10% was accepted as good absolute reliability (Atkinson & Nevill, 1998) and thresholds for *r* were considered moderate (0.3–0.5), strong (0.5–0.7), and very strong (>0.7) (Hopkins, 2000). Normal distribution of data and variance homogeneity between each 15 min interval were assessed using Shapiro–Wilk and a Levene's test, respectively. A repeated measures analysis of variance was used to determine the effect of time for each outcome. To control for family-wise error, post-hoc pairwise comparisons were applied using the Bonferroni correction method. Effect sizes (ES) were calculated using Cohen's *d* and were categorised as small (0.2), medium (0.5), large (0.8) and very large (>1.2) (Fritz et al., 2012).

4.3 RESULTS

All participants provided data for analysis for all outcomes, except for one participant for ventilatory values (owing to claustrophobia) and another for blood analyses (due to haemophobia). The remainder of their data were used.

4.3.1 Reliability of the biomechanical and physiological responses to 120 minutes of soccer-specific exercise

All PlayerLoad™ variables across all time points demonstrated a significant, very strong *r*, except for E1 and E2 for $PL_{M\text{-}L\%}$. All CVs were <8% for all PlayerLoad™ metrics across each time point (Table 4.1). For RER, moderate to very strong (r = 0.33—0.72) correlations were observed during each epoch of which E4, E6, E7 and E8 reached statistical significance. All CVs for RER were <4% irrespective of time point. All time points for $\dot{V}O_{2mean}$ and $\dot{V}O_{2peak}$ (except for E8 for $\dot{V}O_{2mean}$, E5 and E6 for $\dot{V}O_{2peak}$) were >0.70 (*r*), however, both demonstrated good (<7%) CVs.

For all epochs, CVs were lower than 10% and strong or very strong (r = 0.51—0.75) relationships were found between trials for HR_{mean}. Most CVs were >10% for HR_{peak} except E1, E4 and E6, and *r* was less than 0.3 for all epochs excluding E1 and E6. All CVs were <3% for d-RPE values, and RPE-L and RPE-B demonstrated moderate to very strong (0.39-0.88) relationships for all time points except for RPE-L during E2 (0.29) and RPE-B for E4 (0.34). Although RPE-O demonstrated moderate to very strong relationships for six out of eight time points (E1, E1—E8, r = 0.45—0.9), all CVs were <3% throughout the trial (refer to Table 4.1 for significance). Average CVs for CMJ were ~1%, and very strong, significant correlations were detected (>0.9, *r*). CVs were <10% for BLa and only two time points for *r* values were identified as significant ($p \leq .05$).

4.3.2 PlayerLoad™ responses to 120 minutes of soccer-specific exercise

As highlighted in Table 4.1, a main effect for time was observed for PL_{Total} (p = .045) with *post-hoc* analyses revealing that values were higher during E8 compared to E1 (+9.9 ± 5.3%, p = .002, d = 0.8, Figure 4.2). Likewise, a main effect for time was found for PL_V (p = .002) with significant increases observed during E8 (118 ± 19 a.u) compared to E1 (111 ± 16 a.u, d = 0.4). Main effects for time were also identified for $PL_{A\text{-}P}$ (p = .011) with significance identified between E1 (53 ± 7 a.u) and E8 (60 ± 5 a.u, d = 1.2). No time effects were established for $PL_{M\text{-}L}$ (p = .074), $PL_{V\%}$ (p = .703), $PL_{A\text{-}P\%}$ (p = .835) or $PL_{M\text{-}L\%}$ (p = .463).

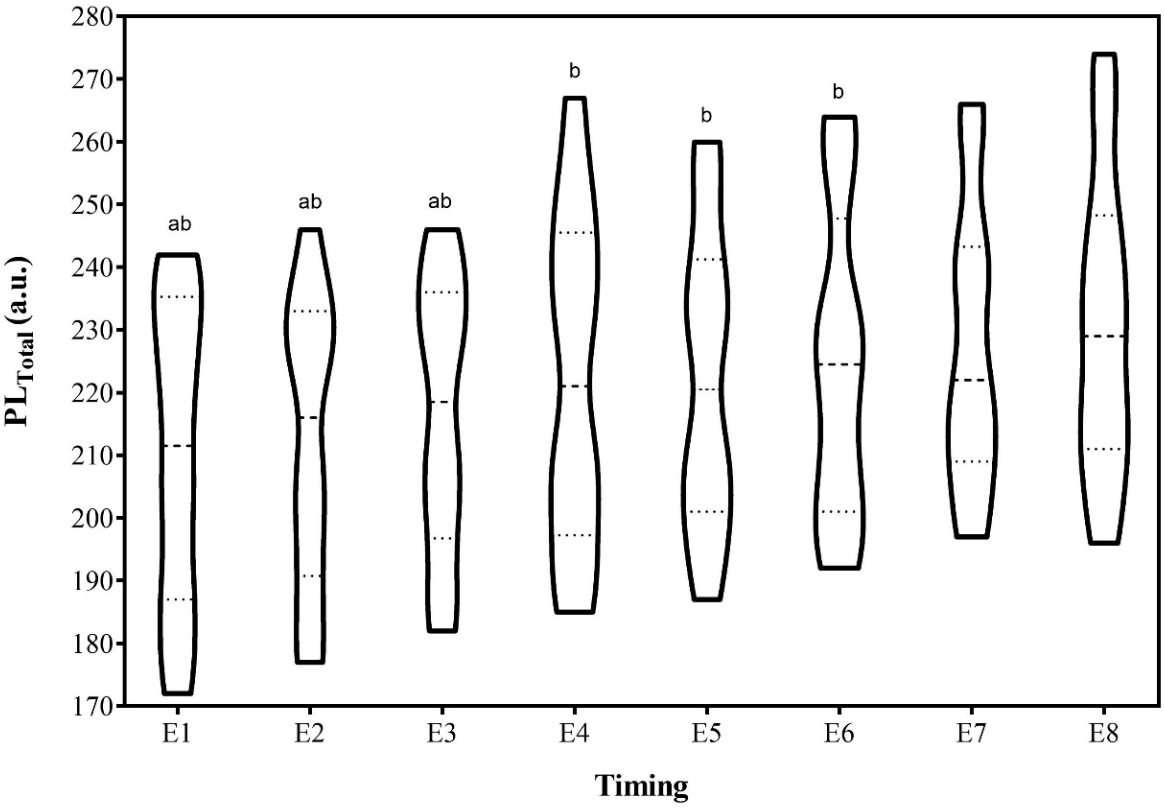

Figure 4.2. Time history changes in PL_{Total} response throughout 120 min of soccer-specific exercise. Data are expressed as mean ± SD. [a] Denotes significant difference compared to E7 for PL_{Total}, [b] denotes significant difference compared to E8 for PL_{Total} (both $p \leq .05$)

Table 4.1. Biomechanical responses throughout 120 min of soccer-specific exercise (mean ± SD)

	Time							
Variable	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**
PL_{Total} (a.u)								
Trial 1	208 ± 27	213 ± 28	217 ± 28	217 ± 27	219 ± 26	220 ± 25	225 ± 22	227 ± 23
Trial 2	215 ± 25[gh]	216 ± 23[gh]	220 ± 22[gh]	226 ± 27[h]	226 ± 24[h]	229 ± 25[h]	230 ± 23[abc]	234 ± 24[abcdef]
Mean	209 ± 25	212 ± 24	217 ± 24	220 ± 26	220 ± 24	222 ± 24	226 ± 22	229 ± 23
CV (%)	5	4.7	4.3	4.1	3.7	2.8	3	3.2
r	0.84	0.86	0.9	0.9	0.91	0.95	0.92	0.91
TE	11.05	10.28	9.5	9.1	8.06	6.15	6.67	7.44
PL_{V} (a.u)								
Trial 1	110 ± 19	112 ± 21	112 ± 21	113 ± 21	113 ± 21	113 ± 21	116 ± 19	116 ± 20
Trial 2	111 ± 16[h]	111 ± 16	113 ± 15	116 ± 20	115 ± 18[g]	116 ± 19	117 ± 18	118 ± 19[a]
Mean	110 ± 17	111 ± 18	112 ± 18	115 ± 20	114 ± 19	115 ± 19	116 ± 18	117 ± 19
CV (%)	4.9	5.5	5.7	4.3	4.1	2.1	2.2	2.4
r	0.91	0.9	0.91	0.95	0.96	0.98	0.98	0.97
TE	5.76	6.89	6.91	4.96	4.66	3.1	2.87	3.47
PL_{A-P} (a.u)								
Trial 1	52 ± 8	54 ± 7	55 ± 7	55 ± 8	57 ± 7	58 ± 7	58 ± 7	60 ± 7
Trial 2	53 ± 7[gh]	53 ± 7[gh]	55 ± 7[gh]	56 ± 8	57 ± 6[h]	58 ± 6[h]	59 ± 6[abc]	60 ± 5[abcef]
Mean	52 ± 7	54 ± 7	55 ± 7	56 ± 7	57 ± 6	58 ± 6	58 ± 6	60 ± 6
CV (%)	6	4.8	3.3	5	4.6	4.3	4	4.9
r	0.86	0.88	0.94	0.9	0.88	0.84	0.89	0.9
TE	3.11	2.62	1.87	2.62	2.45	2.27	2.1	2.3
PL_{M-L} (a.u)								
Trial 1	47 ± 6	47 ± 6	48 ± 6	49 ± 6	49 ± 6	49 ± 6	51 ± 6	51 ± 6
Trial 2	47 ± 7	48 ± 7	49 ± 7	50 ± 7	50 ± 7	50 ± 7	51 ± 7	52 ± 8
Mean	47 ± 6	47 ± 6	49 ± 6	49 ± 6	49 ± 6	50 ± 6	51 ± 6	52 ± 7
CV (%)	7.5	6.1	5.7	5.2	5.4	5.2	4.8	5.2
r	0.75	0.82	0.84	0.85	0.85	0.87	0.89	0.9
TE	3.5	2.85	2.79	2.58	2.6	2.61	2.44	2.65
$PL_{V\%}$								
Trial 1	52 ± 4	52 ± 4	52 ± 4	52 ± 4	52 ± 4	51 ± 4	51 ± 4	51 ± 4
Trial 2	53 ± 3	52 ± 3	52 ± 3	52 ± 4	52 ± 4	52 ± 4	51 ± 4	51 ± 4

Mean	52 ± 3	52 ± 3	52 ± 4	52 ± 4	52 ± 4	51 ± 4	51 ± 4	51 ± 4
CV (%)	1.8	2.5	1.9	1.5	2.1	1.4	0.9	1.6
r	0.94	0.88	0.95	0.96	0.95	0.98	0.99	0.99
TE	0.95	1.34	1.05	0.82	1.09	0.7	0.47	0.77
$PL_{A-P\%}$								
Trial 1	25 ± 4	26 ± 3	26 ± 4	26 ± 4	26 ± 4	27 ± 4	26 ± 4	27 ± 4
Trial 2	25 ± 3[h]	26 ± 3	26 ± 3	26 ± 3	26 ± 3	26 ± 3	26 ± 3	26 ± 3[a]
Mean	25 ± 3	26 ± 3	26 ± 3	26 ± 3	26 ± 3	26 ± 3	26 ± 3	26 ± 3
CV (%)	4.6	3.5	3.2	4.5	3.2	3.7	2.9	2.5
r	0.92	0.95	0.96	0.95	0.96	0.97	0.96	0.98
TE	1.05	0.85	0.79	1.02	0.82	0.87	0.79	0.68
$PL_{M-L\%}$								
Trial 1	22 ± 2	22 ± 2	22 ± 2	22 ± 2	22 ± 2	22 ± 2	23 ± 2	23 ± ± 2
Trial 2	22 ± 1	22 ± 2	22 ± 2	22 ± 1	22 ± 1	22 ± 1	23 ± 1	23 ± 1
Mean	22 ± 1	22 ± 2	22 ± 2	22 ± 2	22 ± 2	22 ± 2	23 ± 2	23 ± 2
CV (%)	5	4.9	4.1	3.5	3	2.8	2.3	1.9
r	0.46	0.56	0.71	0.84	0.88	0.86	0.94	0.96
TE	1.1	1.08	0.93	0.82	0.64	0.67	0.52	0.43

Note. *PL_{Total} = tri- axial playerload; PL_V = vertical playerload; PL_{A-P} anterior/ posterior playerload; PL_{M-L} = medial/ lateral playerload; $PL_{V\%}$ = Percentage contribution of vertical vector; $PL_{A-P\%}$ = percentage contribution of anterior/posterior vector; $PL_{M-L\%}$ = percentage contribution of medial/lateral vector; a.u = arbitrary units; CV = coefficient of variation (%); r = Pearson's correlation coefficient; TE = typical error; E1 = 00:00–14:59 min, E2 = 15:00–29:59 min, E3 = 30:00–44:59 min, E4 = 45:00–59:59 min, E5 = 60:00–74:59 min, E6 = 75:00–89:59 min, E7 = 90:00–104:59 min and E8 = 105:00–119:59 minutes; mean = mean of both trial 1 and 2. Significant differences are only reported for trial 2.*

[a-h] Denotes significant difference from E1-E8 ($p \leq .05$), respectively.

4.3.3 Physiological and physical responses to 120 minutes of soccer-specific exercise

Significant main effects for time were evident for RER (p = .001) with decreases observed during E8 (0.87 ± 0.03 a.u) compared to E1 (0.92 ± 0.02 a.u, d = 2.0). Additionally, HR_{mean} demonstrated a main effect for time (p = .003), with differences identified between E3 (159 ± 16 b·min^{-1}) and E4 (152 ± 16 b·min^{-1}, $p \leq .001$, d = 0.4), as well as E4 and E5 (159 ± 16 b·min^{-1}, p = .003, d = 6.0). No main effects for time were observed for $\dot{V}O_{2mean}$ (p = .407), $\dot{V}O2_{peak}$ (p = .879), HR_{peak} (p = .959) or BLa (p = .203). As outlined in Table 4.2, a main effect for time for both RPE-L (p = .001) and RPE-O (p = .003) was found. For RPE-L, a significant increase was detected from E1 (11 ± 1) to E8 (17 ± 1, $p \leq .001$, d = 6.0) and a similar pattern was evident for RPE-O between E1 (11 ± 1) and E8 (17 ± 2, $p \leq .001$, d = 3.8). No main effects were observed for RPE-B (p = .076). Main effects for time were established for CMJ (p = .020), however, post-hoc comparisons revealed no differences between time points.

No differences were detected for urine osmolality pre (610 ± 132 mOsmoL·kg^{-1}) and post (586 ± 135 mOsmoL·kg^{-1}, p = 0.985, d = 0.2) trial. Once urine-corrected, no significant changes in mass were identified from pre (70.5 ± 8.8 kg) to post trial (69.4 ± 8.5 kg, p = 0.928, d = 0.1).

Table 4.2. Physiological responses throughout 120 min of soccer-specific exercise (mean ± SD)

	Time							
Variable	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**
RER (a.u)								
Trial 1	0.93 ± 0.03	0.92 ± 0.02	0.92 ± 0.02	0.90 ± 0.03	0.91 ± 0.02	0.89 ± 0.03	0.88 ± 0.02	0.88 ± 0.03
Trial 2	0.92 ± 0.02[gh]	0.92 ± 0.02[gh]	0.91 ± 0.02[gh]	0.89 ± 0.02[gh]	0.90 ± 0.02[gh]	0.89 ± 0.02[h]	0.87 ± 0.02[abcde]	0.87 ± 0.02[abcdef]
Mean	0.93 ± 0.03	0.92 ± 0.02	0.91 ± 0.02	0.90 ± 0.02	0.91 ± 0.02	0.89 ± 0.02	0.88 ± 0.02	0.87 ± 0.03
CV (%)	2.9	2.1	2.2	2.9	2.6	2.7	2.1	3.2
r	0.33	0.47	0.42	0.65	0.52	0.71	0.72	0.67
TE	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.02
$\dot{V}O2_{mean}$ (ml·kg^{-1}·min^{-1})								
Trial 1	35 ± 4	34 ± 5	35 ± 5	34 ± 5	34 ± 5	34 ± 5	34 ± 5	34 ± 5
Trial 2	34 ± 4	34 ± 4	34 ± 5	34 ± 4	34 ± 4	34 ± 4	34 ± 4	33 ± 4
Mean	34 ± 4	34 ± 4	34 ± 4	34 ± 4	34 ± 4	34 ± 4	34 ± 4	34 ± 4
CV (%)	2.1	2.1	1.9	1.4	1.6	1.6	1.3	2.4
r	0.78	0.8	0.85	0.9	0.88	0.87	0.91	0.67
TE	2.07	2.06	1.88	1.41	1.59	1.63	1.3	2.35
$\dot{V}O2_{peak}$ (ml·kg^{-1}·min^{-1})								
Trial 1	57 ± 11	57 ± 8	57 ± 10	57 ± 7	59 ± 9	56 ± 6	56 ± 6	58 ± 8
Trial 2	56 ± 8	58 ± 12	58 ± 12	58 ± 11	58 ± 8	57 ± 8	57 ± 8	55 ± 7
Mean	57 ± 10	58 ± 10	58 ± 11	58 ± 9	59 ± 9	57 ± 7	57 ± 7	57 ± 8
CV (%)	4.4	4.1	5.7	5.4	5.5	6.3	3.2	4
r	0.85	0.9	0.79	0.79	0.64	0.29	0.85	0.75
TE	4.29	4.06	5.58	5.22	5.32	6.15	3.61	3.9
HR_{mean} (b·min^{-1})								
Trial 1	154 ± 17	157 ± 19	160 ± 21	152 ± 18	157 ± 22	157 ± 22	160 ± 20	163 ± 18
Trial 2	150 ± 13	154 ± 16	159 ± 16	152 ± 16	157 ± 16	157 ± 16	157 ± 15	159 ± 16
Mean	152 ± 15	155 ± 17	159 ± 18	152 ± 17	157± 18	157 ± 19	158 ± 17	161 ± 17
CV (%)	3.2	6.2	8.8	8.6	8.9	7.2	7.7	5.7
r	0.91	0.77	0.56	0.53	0.59	0.75	0.61	0.77
TE	9.18	9.08	12.84	12.18	13.01	10.68	11.61	8.74
HR_{peak} (b·min^{-1})								
Trial 1	186 ± 26	179 ± 21	179 ± 21	171 ± 22	173 ± 21	181 ± 24	178 ± 23	183 ± 24
Trial 2	179 ± 18	176 ± 19	176 ± 20	175 ± 18	178 ± 23	175 ± 17	180 ± 16	185 ± 15
Mean	182 ± 22	177 ± 19	177 ± 20	173 ± 19	175 ± 21	178 ± 20	179 ± 19	184 ± 20

CV (%)	6	10.2	11	9.9	11.5	9.1	10.6	11.7
r	0.85	0.24	0.19	0.28	0.17	0.43	0.16	-0.02
TE	10.79	17.56	18.79	17	20.01	16.09	18.36	20.3
BLa (mmol·l^{-1})								
Trial 1	2.4 ± 1.0	2.4 ± 1.0	2.1 ± 0.6	2.2 ± 1.2	2.5 ± 1.2	2.6 ± 1.2	2.2 ± 1.0	2.4 ± 1.0
Trial 2	2.4 ± 0.9	2.9 ± 1.5	2.7 ± 1.2	2.3 ± 0.9	3.0 ± 1.3	3.8 ± 2.7	2.7 ± 0.9	2.4 ± 1.1
Mean	2.4 ± 0.9	2.6 ± 1.2	2.4 ± 0.9	2.4 ± 1.0	2.8 ± 1.2	3.3 ± 2.1	2.6 ± 0.9	2.4 ± 1.0
CV (%)	0.8	0.9	0.7	0.5	0.7	1.8	0.6	0.6
r	0.39	0.5	0.57	0.82	0.74	0.39	0.68	0.71
TE	0.77	0.94	0.7	0.51	0.67	0.78	0.57	0.6
RPE-L (a.u)								
Trial 1	11 ± 1	11 ± 1	12 ± 1	13 ± 1	14 ± 1	15 ± 1	15 ± 1	17 ± 1
Trial 2	11 ± 1^{gh}	11 ± 1^{gh}	12 ± 1^{gh}	13 ± 1^{gh}	14 ± 1^{gh}	15 ± 1^{gh}	15 ± 1^{abcdefh}	17 ± 1^{abcdefg}
Mean	11 ± 1	11 ± 1	12 ± 1	13 ± 1	14 ± 1	15 ± 1	15 ± 1	17 ± 1
CV (%)	0.7	2.1	1.9	1.8	0.7	0.7	1.6	1.5
R	0.64	0.29	0.61	0.39	0.61	0.87	0.64	0.78
TE	0.64	0.77	0.51	0.82	0.74	0.41	0.68	0.59
RPE-B (a.u)								
Trial 1	11 ± 1	12 ± 1	12 ± 1	13 ± 1	14 ± 1	14 ± 1	15 ± 2	16 ± 2
Trial 2	11 ± 1^{gh}	12 ± 1^{gh}	12 ± 1^{gh}	13 ± 1^{gh}	14 ± 1	14 ± 1	15 ± 2^{abcd}	15 ± 2^{abcd}
Mean	11 ± 1	12 ± 1	12 ± 1	13 ± 1	14 ± 1	14 ± 1	15 ± 2	16 ± 2
CV (%)	0.7	1.8	0.7	0.7	0.7	0.7	1.5	0.7
r	0.75	0.44	0.39	0.34	0.64	0.68	0.88	0.86
TE	0.55	0.84	0.77	0.96	0.82	0.84	0.76	0.86
RPE-O (a.u)								
Trial 1	11 ± 1	12 ± 1	13 ± 1	13 ± 1	14 ± 1	15 ± 1	14 ± 1	16 ± 1
Trial 2	11 ± 1^{gh}	11 ± 1^{gh}	12 ± 1^{gh}	13 ± 1^{gh}	14 ± 1^{gh}	15 ± 1^{gh}	15 ± 2^{abcdefh}	17 ± 2^{abcdefg}
Mean	11 ± 1	12 ± 1	12 ± 1	13 ± 1	14 ± 1	15 ± 1	16 ± 1	17 ± 1
CV (%)	2.1	0.7	0.7	0.7	0.7	0.7	1.4	0.7
r	-0.09	-0.18	0.23	-0.09	0.47	0.85	0.88	0.91
TE	1.04	0.93	0.77	1.06	0.77	0.47	0.56	0.47
	Pre-trial	**Post HT**	**Pre 2nd half**	**90 min**	**120 min**			
CMJ (cm)								
Trial 1	35.2 ± 6.3	36.0 ± 6.4	33.9 ± 6.8	36.5 ± 7.2	34.2 ± 8.5			

Trial 2	35.4 ± 7.1	36.5 ± 7.4	34.6 ± 7.9	36.8 ± 7.7	34.3 ± 8.4
Mean	35.3 ± 6.4	36.2 ± 6.6	34.3 ± 7.1	36.6 ± 7.1	34.2 ± 8.1
CV (%)	0.8	0.7	1.1	0.9	0.7
r	0.93	0.94	0.92	0.99	0.99
TE	1.96	1.98	2.27	0.8	1.04

Note. RER = respiratory exchange ratio; V̇O2 = oxygen consumption; HR = Heart rate; BLa = blood lactate; RPE = Ratings of perceived exertion; RPE-L = RPE legs; RPE-B = RPE breathlessness; RPE-O = RPE overall; CMJ = countermovement jump height; a.u = arbitrary units; CV = coefficient of variation (%); r = Pearson's correlation coefficient; TE = typical error; E1 = 00:00–14:59 min, E2 = 15:00–29:59 min, E3 = 30:00–44:59 min, E4 = 45:00–59:59 min, E5 = 60:00–74:59 min, E6 = 75:00–89:59 min, E7 = 90:00–104:59 min and E8 = 105:00–119:59 minutes; mean = mean of both trial 1 and 2. Significant differences are only reported for trial 2.

[a-h] Denotes significant difference from E1-E8 ($p \leq .05$), respectively.

4.4 DISCUSSION

The aim of this study was to investigate the reliability of the biomechanical and physiological responses to 120 min of treadmill-based soccer-specific exercise. In accordance with the sudy hypotheses, the test-retest reliability for most of the variables was moderate-to-very-strong for relative reliability (i.e., *r*) and good for absolute reliability (i.e., CVs). Biomechanical performance was also negatively impacted as a function of time, with further increases identified for PL_{Total} during the final 30 min of exercise. Furthermore, increases in d-RPE and the rate of fat oxidation as measured via indirect calorimetry were observed during ET. Therefore, evidence suggests the current treadmill simulation can be used to elicit repeatable responses across 120 min of soccer-specific activity to profile the change in biomechanical and physiological fatigue.

The PlayerLoad™ responses for the current study demonstrated good CVs (0.9—7.5%) across all metrics throughout the 120-min protocol duration. Comparatively, previous convergent validity analysis by Berreira and colleagues assessing two sessions of a free-running soccer exercise simulation demonstrated higher CVs for PlayerLoad™ between trials (14.5—24.5%) (Barreira et al., 2017). It is possible that the differences in reliability are largely associated with the type of exercise simulation utilised and the familiarisation session in both studies. Considering the distances and speeds were standardised in the current treadmill-based exercise, and that participants were required to sustain standardised speeds to remain on the treadmill, it is likely that this accounts for the greater reliability of the biomechanical responses. On the other hand, the intensity of a free-running simulation is dictated by verbal signals on an audio track and participants have neglible obligation to reach the externally-paced speeds (Barreira et al., 2017). This could lead to inconsistencies with reference to the speeds and distances performed, the fatigue profile and as such, elicit less reliable responses. Furthermore, the participants in the current study performed a full 120 min familarisation prior to trials 1 and 2. This may have reduced learning effects by habituating participants with the instantaneous acceleration of the treadmill and enabled them to execute a smooth transition (reducing jerk) between stationary and running activity. However, insufficient detail of the familiarisation protocol was provided for the free-running investigation, thus, could be a factor influencing the varied PlayerLoad™ responses between trials (Barreira et al., 2017).

There was no systematic bias between exercise trials for BLa (CV ≤ 1.8%), despite the innate variability associated with blood sampling, physiological stress and fatigue parameters (Meister et al., 2014). These values largely conflict with previous ET research using the Soccer Match Simulation (Harper et al., 2016d), which elicited slightly higher BLa values, coupled with much larger CVs for BLa (14.0—26.8%) (Harper et al., 2016d). The highly variable BLa values could be partly attributed to the technical actions that are typically absent within treadmill protocols and the sample population used for the study. The investigation utilised university-standard players, with participants possibly possessing a reduced technical ability and incapable of retaining ball control. It has been argued that the lack of skill may influence the exercise intensity of the protocol (Russell & Kingsley, 2011). Such inconsistencies in technical ability may, in-turn, compromise the repeatability of the physiological response, thus, explaining the marked differences in BLa CVs between studies. To date, the current soccer-specific exercise protocol is the only treadmill-based simulation to be deemed reliable over 120-min. Therefore, this presents a reliable alternative to the Soccer Match Simulation (Harper et al., 2016d), especially if researchers have logistical issues, such as limited space. Therefore, given the low test-retest error, the current simulation may be preferable as a reliable exericse stimulus to evaluate the biomechanical and physiological fatigue response.

The test-retest reliability for an outcome variable can influence the sample size required to detect a change across a repeated measures experiment (Batterham & Atkinson, 2005). In line with previous soccer investigatons (Aldous et al., 2014; Harper et al., 2016d; Sirotic & Coutts, 2008), Batterham and Atkinsons nomogram has been used to estimate the required sample size (Batterham & Atkinson, 2005). Using the nomogram to interpret the current RER, $\dot{V}O2_{mean}$, BLa, CMJ and d-RPE data (all ≤ 5%), it is estimated that a sample size of between 5 and 10 is adequate to detect a 5–10% change. It was also established that the ventilatory measures (RER, $\dot{V}O2_{mean}$ and $\dot{V}O2_{peak}$) were moderate-to-very strongly reliable (r = 0.33—0.91) and demonstrated good absolute reliability (CVs = 1.3—5.7%). Breathing measurements recorded during previous intermitent exercise protocols (Sirotic & Coutts, 2008) have shown to be highly variable versus steady-state treadmill exercise (Saunders et al., 2004). However, the current protocol elicited lower RER measurement variability (TE = 0.01—0.02 au) compared with the aforementioned steady-state treadmill-based running (TE = 0.03—0.04 au) (Saunders et al., 2004). Therefore, the above data yield confidence that the present simulation is sensitive enough to detect a ‘true’ change (outside the measurement error) in RER given that the study recruited a sample size of 12. This also supports that the signficant RER reductions observed during ET can be considered practically meaningful and not related to the error and/or variation associated with testing.

To date, evidence suggests that the physical capacity of players is reduced during ET matches (Peñas et al., 2015; Russell et al., 2015b; Winder et al., 2018). However, caution should be applied when interpreting match-play observations as they do not account for contextual variables (Abbott et al., 2018b) such as stoppages in play and altered tactical approaches. However, in the present study, the use of a treadmill simulation enabled the standardisation of running output, thus allowing for any observed changes to be attributable to changes in a player's capacity to cope with the fixed treadmill activity. As such, any observed changes in PlayerLoad™ can be attributable to a compromised movement efficiency rather than modifications to the activity and locomotion profile performed (Page et al., 2015).

Page et al. (2015) assessed PlayerLoad™ responses across 90 min of treadmill-based, soccer-specific bouts of identical bouts of repeated activity. The authors reported increases in PL_{Total}, concurrent with reductions in $PL_{V\%}$ as a function of exercise duration. Similarly, previous match-play observations found a reduction in the vertical contribution of PlayerLoad™ in Australian rules football players (Cormack et al., 2013). Consistent with the two studies above, the present data suggests a similar temporal pattern, which, although not directly measured in the current study, may be indicative of an attempt to conserve energy by adjusting stride length or frequency, or both, which could in turn reduce running efficiency (Hobara et al., 2009). It appears that when fatigued, individual running patterns become biomechanically less efficient, which can cause additional stress to joints, tendons and ligaments (Wilk et al., 2009). Furthermore, the modifications in vertical movement as seen in the present research have previously been associated with reductions in lower extremity stiffness (Buchheit et al., 2015).

Several studies have measured the elastic properties of muscle and tendon using shear wave ultrasound elastography (Akagi & Takahashi, 2014; Maïsetti et al., 2012; Zhang et al., 2015b). Shear wave ultrasound elastography is a valid and reliable tool for quantifying stiffness of skeletal muscle (Kot et al., 2012; Zhang & Fu, 2013), although, this method is expensive and requires skilled expertise (Feng et al., 2018). Therefore, indirect measures have been used to quantify leg stiffness from rebound jump actions and subsequent flight and ground contact times (Lloyd et al., 2009). However, although the relationship between stiffness and performance is well-established, much less is known about the interaction associated with stiffness and injury (Butler et al., 2003). It is believed that disproportionate levels of stiffness can lead to an increased injury-risk to the lower extremities (Pruyn et al., 2012). From the current data it can be speculated that participants displayed less vertical displacement as a function of exercise duration, indicative of a reduced vertical stiffness and increased risk to soft tissues (Hughes & Watkins, 2008). However, during matches, it is likely that in a subconscious attempt to avoid injury, players will reduce running output, in turn impacting physical performance. In support of a potential reduction in performance, impaired movement efficiency may also manifest in a reduced ability to maintain high-speed output, in-turn reducing a team's ability to score goals. To corroborate this suggestion, it has been suggested that 45% of goals in the German Bundesliga were preceded with straight line sprints (Faude et al., 2012). Therefore, a reduced capacity during ET may result in fewer matches decided during this period, and as such, preparing players for the additional 30 min duration associated with ET may reduce injury-risk and increase physical performance, ultimately increasing team success.

Another novel feature of this study was the measurement of substrate utilisation via indirect calorimetry across 120 min of soccer-specific exercise. An RER of 1.0 indicates 100% carbohydrate oxidation (i.e., glycolysis), whilst a value of 0.70 indicates 100% fatty acid oxidation (i.e., lipolysis), with 0.85 a.u indicating an equal contribution. According to the current data and corresponding with previous ET research (Stevenson et al., 2017), players utilise both fat and carbohydrate to fuel soccer exercise, however, fat oxidation increases during ET. Despite observing a shift towards lipolysis and a downregulation in glycolysis, the RER values during ET (0.87 a.u) suggest that carbohydrate is still being utilised. Furthermore, as participants appeared less efficient across bouts (i.e., increased energy cost to produce the same activity — although speculative as energy output was not directly measured), it was surprising to find a ~29% reduction (although non-significant) in BLa concentrations between E6 and E7 (Figure 4.3). This further supports that glucose levels were potentially depleted and less was available to undergo biotransformation during ET under anaerobic conditions.

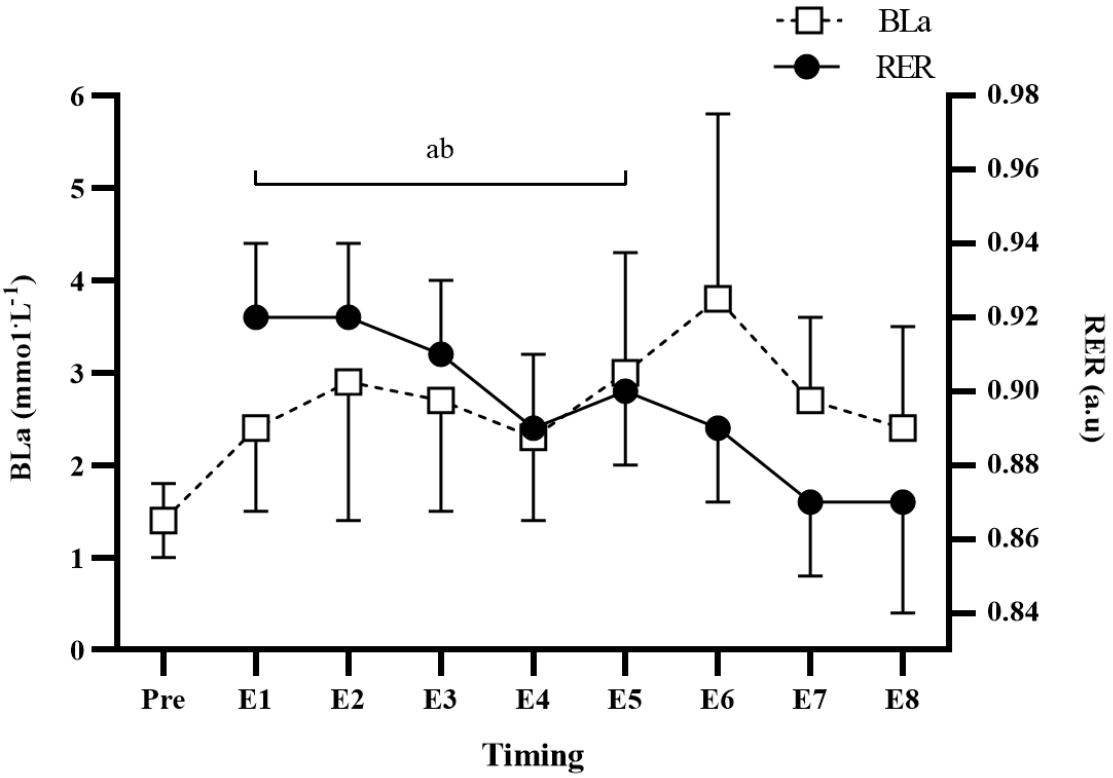

Figure 4.3. Mean RER and BLa concentrations across 120 min for each 15-min period of soccer-specific exercise. Data are expressed as mean ± SD. [a] Denotes significant difference from E7 for RER. [b] Denotes significant difference from E8 for RER ($p \leq .05$)

Prior to the main trials, participants in the current research were not required to consume a pre-match meal as done in a previous investigation that has attempted to measure changes in substrate use (Stevenson et al., 2017). Therefore, this methodological discrepancy limits comparison between studies as participants in the current study may have completed exercise with lesser endogenous carbohydrate at baseline. Furthermore, within-match carbohydrate consumption is customary for soccer players (Anderson et al., 2016) and participants in the present research were limited to solely water intake. Evidence shows that exercising without exogenous carbohydrate ingestion results in inherent increases in the oxidation of plasma FFA (Gribok et al., 2016), however this is largely influenced by exercise intensity and duration, among other factors (Luc et al., 2001). Accordingly, further investigations examining the effect of carbohydrate supplementation across 120 min of soccer-specific exercise are warranted.

The present results indicate that the soccer-specific exercise imposed the most considerable load on RPE-L with scores reaching 17 ± 1 during ET, equating to the verbal anchor 'very hard' according to the Borg scale. This finding is consistent with other work whereby RPE-L was highest during aerobic exercise (Borg et al., 2010) and ~30 min post soccer match-play (Weston et al., 2015). However, given this study is the first to employ a within soccer-specific exercise approach to measuring d-RPE, it is difficult to compare the current findings directly to other literature; therefore, this research may be used to inform future investigations that measures within-match changes in d-RPE. Furthermore, d-RPE typically increased as a function of exercise duration and was reliable between sessions (CV ≤ 2.1%). This suggests that d-RPE can be used to reliably assess internal load during soccer-specific exercise and may be a feasible tool to differentiate player exertion to assist in tailoring training programmes (Macpherson et al., 2019).

4.5 CONCLUSIONS

Within the scope of the limitations, the findings of the current study add to an expanding body of ET literature. The test-retest reliability of the biomechanical and physiological responses to the current 120-min treadmill-based soccer-specific exercise protocol were deemed to have moderate-to-very strong reliability. Therefore, the treadmill-based protocol may be adopted for various purposes, including reliably investigating the effectiveness of nutritional interventions, the impact of differing climatic and environmental conditions on soccer performance and for player rehabilitation. The data also demonstrated a temporal shift in predominant energy pathway utilisation (i.e., aerobic glycolysis to fat oxidation) during 120 min of soccer-specific exercise. Likewise, changes in PlayerLoad™ throughout 120 min of soccer-specific exercise were evident, with further fatigue-induced changes identified during ET. This study took a novel approach to investigating soccer-specific exercise over 120 min, that is, utilising a standardised activity profile to assess fatigue responses. Based on these findings, it is postulated that the reduced mechanical efficiency observed may hold fatigue-induced injury-risk implications for players during this period of match-play. However, the extent to which the additional demands associated with ET contribute to injury prevalence may be required through the longitudinal surveillance of soccer players. It is recommended that practitioners condition players to be able to cope with the additional 30 min of competition to minimise injury occurrence, although the contemporary issue of fixture congestion may limit time to do so. Therefore, at which stage during the season this is developed and maintained must be considered. This research also confirms the importance of carbohydrate consumption during soccer matches to maintain the glycolytic process, which may assist with offsetting the impact of fatigue. However, the origins of fatigue are not well understood during and following the ET period of soccer. Therefore, further research is required to explore the relative contributions of peripheral and central processes to fatigue during and following 120-min of soccer-specific exercise.

5.0 LOWER-LIMB MUSCLE EXCITATION, PEAK TORQUE AND EXTERNAL LOAD RESPONSES TO 120 MINUTES OF TREADMILL-BASED SOCCER-SPECIFIC EXERCISE

Publication arising from this chapter:

Field, A., Page, R. M., Corr, L. D., Naughton, R. J., Haines, M., Harper, L. D., & Hudson, S. (2020). Lower-limb muscle activation, peak torque and external load responses to a 120-minute treadmill-based soccer-specific simulation. Research Quarterly for Exercise and Sport, 1-11.

Author contributions

Adam Field wrote the manuscript, and collected all data. Adam Field carried out statistical analyses and Richard Michael Page assisted. All authors reviewed the manuscript at various stages throughout the editing process. All authors read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

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5.0.1 ABSTRACT

The aim of this study was to investigate thigh muscle excitation and peak torque in response to soccer-specific exercise incorporating an ET period. Twelve semi-professional soccer players performed a 120-min treadmill-based soccer-specific exercise protocol. Surface EMG signals for the rectus femoris (EMG_{RF}) and biceps femoris (EMG_{BF}) were measured as the mean response across a pre-determined 10-s sprint bout during each 15-min block of exercise. Peak eccentric torque of the knee flexors (eccKF) and concentric torque of the knee extensors (conKE) were recorded across angular velocities of 60, 180, and 270 deg·s^{-1} immediately pre- and post-exercise. Tri-axial PlayerLoad™ (PL_{Total}) was monitored throughout exercise and defined as PL_{V}, $PL_{A\text{-}P}$, and $PL_{M\text{-}L}$ planes of motion. A reduction in normalised EMG_{RF} amplitude was evident at 105–120 min, versus 0–15 min (−12.5%; p = .037), 15–30 min (−12.5%; p = .047), and 45–60 min (−14%; p = .030). Peak torque of the eccKF was significantly reduced from pre- to post-exercise at 60 (−7.7%; p = .018), 180 (−10.5%; p = .042), and 270 deg·s^{-1} (−7.5%; p = .034). A main effect for time was identified for PL_{Total} (p < .010), PL_{V} (p = .033), and $PL_{A\text{-}P}$ (p < .010). These findings suggest that muscle activation of the rectus femoris is reduced during ET, accompanied with a deficit in the torque generating potential of the knee flexors following 120 min of soccer-specific activity. Practitioners should adequately condition players for the additional ET period by incorporating exercises into training schedules that develop fatigue-resistant eccentric hamstring strength to minimise injury risk.

5.1 INTRODUCTION

Soccer is characterised by an intermittent activity profile, involving rapid CoD tasks, accelerations, decelerations, and sprints. While soccer is traditionally competed over 90 min, several tournaments (e.g., FIFA World Cup, UEFA Champions League and English FA Cup) proceed to an additional 30 min period known as ET when scores are tied. Notably, during the previous four FIFA World Cup competitions 33% of knockout phase matches have proceeded to ET, with 50% requiring 120 min of match-play at the 2014 FIFA World Cup competition. It was identified in Chapter 4 that biomechanical and physiological fatigue occurs during ET when players perform fixed bouts of soccer-specific exercise. It is likely that these performance decrements are exercise induced and the biomechanical and physiological changes are as a result of peripheral and central fatigue-related processes (Brownstein et al., 2017; Thomas et al., 2017). However, these origins of fatigue are not well understood during and following 120-min of soccer-specific activity.

Peripheral fatigue corresponds to processes associated with mechanical and cellular changes occurring at or distal to at the neuromuscular junction, and is perhaps related to excitation–contraction coupling, metabolite accumulation and substrate depletion (Schillings et al., 2003). Central fatigue manifests in the central nervous system; reducing activation of motor neurons, which can result in diminished muscular activation (Brownstein et al., 2017; Thomas et al., 2017). Although it is difficult to entirely differentiate the contribution of each of these fatigue sources, 89% of force loss can be attributed to peripheral factors (Schillings et al., 2003). Therefore, force quantification is often used as a close approximation of peripheral fatigue development. Direct measures of central fatigue can be ascertained via twitch interpolation techniques (Shield & Zhou, 2004) and transcranial magnetic simulation (Thomas et al., 2015). However, these measurement procedures are difficult to adopt during dynamic exercise such as soccer-specific activity. It must also be noted that measuring the precise origin of fatigue is difficult due to the complex interaction of the biological and psychological processes, and as such several indirect methods of assessment are often used such as subjective scales (Harper et al., 2016d), physical performance indices (Goodall et al., 2017; Thomas et al., 2017) and muscle activation measurements (Page et al., 2019; Rahnama et al., 2006).

Previous research suggests that simulated and actual match-play elicits a deficit in knee extensor force production (peripheral fatigue), alongside a reduction in neural drive from the central nervous system (central fatigue) (Brownstein et al., 2017; Thomas et al., 2017). It has also been observed that 120 min of simulated soccer causes peripheral and central patterns of fatigue, with additional reductions in voluntary muscle activation identified during ET, indicating fatigue during this additional period may be primarily of central origin (Goodall et al., 2017). However, the exact within-match fatigue source has yet to be investigated across 120 min of soccer-specific exercise. Furthermore, the reduction in lower-limb force production following prolonged intermittent activity has been linked with modified twitch contractility properties that can impair torque production and changes in muscle excitation measured through an EMG signal (Rahnama et al., 2006; Rahnama et al., 2003). It has been demonstrated that 90-min treadmill-based soccer activity elicits muscle contractile deficits in knee extensors and flexors (Rahnama et al., 2003), and changes in muscle excitation of the lower limbs, measured via surface EMG (Rahnama et al., 2006). A reduction in excitation of the lower-limb muscles appears to be further exacerbated by repeated bouts of a soccer simulation with minimal recovery, mimicking fixture congested periods of match play (Page et al., 2019). Furthermore, while marked strength deficits occur across prolonged exercise durations (Goodall et al., 2017), the extent to which potentiation of twitch contractile properties (Requena et al., 2011) and coactivation of lower-limb synergist muscles (Saito et al., 2013) play a role in counteracting fatigue-induced strength decrements remains elusive. Thereby, while there appears to be a detrimental effect of completing 90 min of soccer-specific exercise and simulated fixture congestion on muscle excitation, no previous studies have assessed the potentially deleterious impact of an ET period on muscle excitation measured using surface EMG.

Measuring changes in EMG activity throughout prolonged intermittent activity can improve understanding of the alterations in neural input to the muscles and subsequent patterns of fatigue (Albertus-Kajee et al., 2011). To enhance interpretations of the changing muscle activation patterns across exercise, quantifying the between-session reproducibility of the methods and error of measurement associated with the instruments for assessing EMG activity must be considered and ideally reported (Besomi et al., 2020). Previous research has investigated the reproducibility of adopting EMG assessment methods to assess changes in neural activity in female long distance runners across three running speeds (9.0, 10.8 and 12.6 $km \cdot h^{-1}$) (Karamanidis et al., 2004). The data revealed that measuring EMG parameters are reliable for the gastrocnemius medialis and lateralis (ICCs > 0.69 for 73% of data), although the vastus lateralis, hamstrings and tibialis anterior were deemed less reliable. In a separate study, high inter-, but low intra-individual CVs were found for EMG measures recorded during continuous (4.2 ms^{-1}) treadmill running (Guidetti et al., 1996). However, there are no investigations that report the reproducibility of EMG assessment methods across intermittent exercise modalities. Therefore, the changes in EMG activity across intermittent exercise protocols must be interpreted with caution as the repeatability of such methodologies are largely unknown.

Microsensor technology placed at the upper trunk has yet to be validated in relation to quantifying injury-risk and sport-specific movements (Chambers et al., 2015). Similarly, it is contentious as to whether the within-match changes in PlayerLoad™ and discrete planar contributions are reflective of running patterns in relation to specific lower-limb musculature (Cormack et al., 2013; Verheul et al., 2020). Additionally, the devices that are used to measure PlayerLoad™ in an applied soccer setting, typically involves placement in a vest worn by players. Therefore, PlayerLoad™ has more application in a sporting context due to the ease of measurement compared with less feasible alternatives such as EMG and isokinetic peak torque measures. Therefore, assessing PlayerLoad™ metrics in conjunction with excitation and torque responses of major lower-limb muscles appears warranted to provide practically compatible alternatives. This will in turn facilitate understanding of whether PlayerLoad™ changes correspond with local fatigue patterns of thigh musculature during prolonged intermittent activity.

In light of the above, the aim of the present study was to assess thigh musculature excitation and peak torque production, as well as changes in PlayerLoad™ metrics in response to 120-min of treadmill-based soccer-specific exercise. It was hypothesised that ET would reduce the degree of excitation and torque production of the thigh musculature, and that this additional 30 min period would elicit increases in PlayerLoad™ values.

5.2 METHODS

5.2.1 Participants

Institutional ethical approval was granted, and the study adhered with the most recent version of the Declaration of Helsinki. Twelve semi-professional soccer players (mass: 74 ± 8 kg; stature: 179 ± 3 cm; age: 22 ± 3 years; $\dot{V}O_{2max}$: 59 ± 7 ml·kg·min^{-1}) provided written informed consent. An *a priori* power calculation was undertaken (G*Power©, version 3.1.9.2, 2017, Germany) which deemed a sample size of 11 sufficient based on 95% 1 − β, an α of .05, and a large ES (Cohen's d = 1.1) to detect significant differences for EMG based on previous data (Page et al., 2019). Participants were recruited on the basis they were male with > 5 years of soccer experience and had no medical contraindications to exercise (e.g., musculoskeletal injury). Participants visited the laboratory on three separate occasions and were asked to avoid strenuous exercise external to the study throughout the testing period. Participants refrained from caffeine for 12 hr and alcohol 24 hr prior to testing. Mean participant energy and macronutrient intake was recorded across the 24-hr period prior to testing through use of weighed food diaries (energy: 1998 ± 490 Kcal, carbohydrates: 218 ± 66 g, protein: 111 ± 45 g, fat: 75 ± 19 g).

5.2.2 Preliminary visits and study design

The preliminary visit involved taking anthropometric measures of stature (SECA 213 portable stadiometer, SECA, Germany) and mass (SECA 875 electronic flat scale, SECA, Germany), and the completion of a $\dot{V}O_{2max}$ test. This involved a graded ramp test until volitional exhaustion to assess participant's eligibility (see section 3.8.1 for further details). A secondary visit was used for familiarisation, which included a full habituation of experimental procedures including the completion of a 120 min simulation. This was preceded by a standardised treadmill-based warm-up that comprised 10 min of aerobic activity with multiple sporadic speed changes and a dynamic stretching sequence. One week thereafter, the third and final visit involved the main trial. This included the 120 min soccer simulation following the completion of the same warm-up as described above. During the main trial breaks (HT, full-time and ET mid-interval), *ad libitum* intake of a carbohydrate–electrolyte solution was permitted (Lucozade Sport, GlaxoSmithKline, Gloucestershire, UK). Participants ingested a mean of 729 ± 28 ml.

5.2.3 Soccer simulation

The soccer simulation was performed on a treadmill (h/p/ cosmos pulsar® 3p: h/p/cosmos sports & medical GmBH, Germany) consisting of eight 15 min periods, with a HT period interspersing the 3rd and 4th and a 5 min passive rest interspersing the 6th and 7th periods. The protocol was validated alongside 90-min of match-play (Page et al., 2015). Two additional bouts were incorporated for the ET period, with the PlayerLoad™ responses demonstrating very strong reliability over 120 min (r = 0.75–0.92, Chapter 4). Participants completed 16.26 km during the 120-min protocol (Chapter 4) with the activity profile designed to replicate the velocities, durations, and frequencies of speed changes associated with match-play (Page et al., 2015). The simulation repeated the same fixed activity profile every 15 min, and data were analysed accordingly. The 120 min simulation was divided into eight epochs including: E1 (00:00–14:59 min), E2 (15:00–29:59 min), E3 (30:00–44:59 min), E4 (45:00–59:59 min), E5 (60:00–74:59 min), E6 (75:00–89:59 min), E7 (90:00–104:59 min), E8 (105:00–119:59 min).

5.2.4 Surface electromyography

The EMG signal of the rectus femoris (EMG_{RF}) and biceps femoris (EMG_{BF}) of the dominant leg (defined as the preferred kicking leg) were recorded using wireless surface EMG sensors (Inter-electrode distance 10mm; Trigno™, Delsys, USA). In accordance with recommendations for surface EMG sensor placement procedures (Stegeman et al., 2000), the skin was shaved and cleaned prior to electrode attachment to reduce impedance. To ensure that movement artefacts were minimal, the electrodes were carefully taped to the skin using surgical tape. The EMG activity was recorded at 2000Hz and processed using Delsys software. In accordance with previous methods (Page et al., 2019), the EMG signal was recorded over a single 10-s action within each 15-min bout of the soccer simulation to capture the myoelectric activity for the entire acceleration and deceleration phase (running velocity of 25 $km \cdot h^{-1}$; Figure 5.1). This specific action was chosen in accordance with the injury etiology of the knee flexors being mainly associated with the deceleration stage during the late swing phase of sprinting (Chumanov et al., 2012; Setuain et al., 2017).

Locomotion Category (velocity)	n	Duration (s)	Gradient (%)
Standing (0 $km \cdot h^{-1}$)	29	7.0	1.0
Walking (4 $km \cdot h^{-1}$)	65	6.4	1.0
Jogging (8 $km \cdot h^{-1}$)	53	3.0	1.0
Low Speed running (11.6 $km \cdot h^{-1}$)	48	2.6	1.0
Moderate speed running (15 $km \cdot h^{-1}$)	17	2.2	2.0
High Speed Running (18 $km \cdot h^{-1}$)	12	2.1	2.0
Sprint (25 $km \cdot h^{-1}$)	7	2.0	2.5

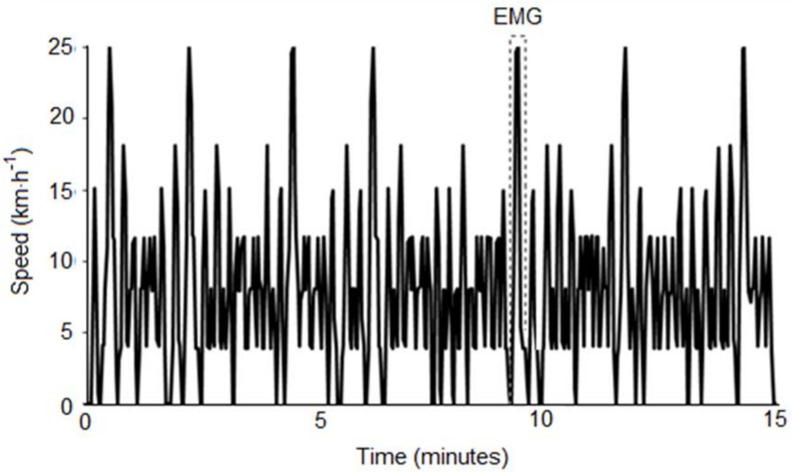

Figure 5.1. Schematic of the activity profile of an individual 15 min bout of the soccer-specific simulation. The dashed line indicates the 10-s period by which electromyography data was collected.

To process the EMG data, the raw EMG signals were low pass filtered at 500Hz and high pass filtered at 10Hz to preclude movement artefacts, using a Butterworth fourth order filter. The signal was then rectified and smoothed using a root mean square (RMS) smoothing factor with a 50-ms time constant (Hader et al., 2014). The mean RMS value was obtained for each 10-s recording to quantify the mean EMG (the degree of muscle excitation) for each bout of the soccer simulation (Page et al., 2019; Rahnama et al., 2006). The amplitude mean was analysed as opposed to the single peak data point because it is a more stable reference value, and less sensitive to duration differences across intervals (Konrad, 2005). The EMG signal recording for the pre-determined sprint during E1 was used as the reference value for normalisation of E2–E8. Similar to previous methods (Pincivero et al., 2000), a decision was taken to normalise against the first sprint because participants were likely in a less fatigued state during the initial bout of activity and sprint measures are more functionally relevant than an isolated maximal voluntary contraction. The normalised EMG data were expressed as a percentage of the mean value obtained during E1. This method was undertaken in accordance with recommendations for the normalisation of EMG amplitudes (Besomi et al., 2020).

5.2.5 Isokinetic testing

Peak eccentric torque of the knee flexors (eccKF) and peak concentric torque of the knee extensors (conKE) were measured immediately post warm-up and post-exercise using the Cybex HUMAC Norm isokinetic dynamometer with HUMAC2009 software version 0.8.4 (CSMI, USA). Fatigue induced knee flexor strength deficits are commonly observed during the latter stages of simulated and actual match-play (Greig, 2008; Small et al., 2010). During the eccentric phase of contraction, injury risk is heightened as fatigued muscles are more likely to suffer stretch injuries due to an impaired capacity to resist over lengthening (Croisier et al., 2008; Opar et al., 2012). The synergy of the eccKF and conKE seems to better replicate the functional movements performed throughout a soccer match (i.e., soccer kicking actions) compared to alternative knee extension and flexion interactions (Magalhaes et al., 2004). The preferred kicking leg was tested at three angular velocities of 180, 270 and 60 $deg \cdot s^{-1}$. This specific order was used to reduce potential fatigue induced by slower velocities (Greig, 2008). One set was performed for each speed (i.e., a total of three sets) which included five repetitions completed through a range of 0−90° (0° equal to full extension) and were interspersed by a 30-s passive rest period. Once seated, participants were secured, and the contralateral limb was isolated as per manufacturer guidelines. To account for the influence of the participants limb weight to subsequent torque generation, the HUMAC2009 software automatically performs a gravity correction procedure. This involves the participant’s passive limb being weighed at anatomical zero (defined as full knee extension). The limb is working against gravity (i.e., eccentric knee flexor and concentric knee extensor work involves an upward motion) and, as such, the limb weight contribution value for each participant is subsequently added as a constant value to their torque curves.

5.2.6 PlayerLoad™

PlayerLoad™ metrics were defined as the accumulated mean value across each 15 min block of exercise (see section 3.8.2 for specific details). The same device was used between simulations as intra-device test-retest has demonstrated good reliability as evidenced by low coefficient of variations (CV: 0.01–3.0%) and intra-class-correlations (ICC: 0.77–1.0; Nicolella et al. (2018)).

5.2.7 Statistical analyses

Eight EMG data points were absent across six participants due to technical difficulties with the wireless recording, though all other data were presented for analyses. Linear mixed modelling (LMM) is appropriate for repeated measures designs that involve random and fixed level factors with missing data; assuming data are missing at random (Di Salvo et al., 2009). As such, LMM analysis was employed for the current study. Initially, the normality of residuals was checked through visually examining q-q plots, boxplots and histograms, and residuals > 3.0 SD from the mean were removed. Within-subject LMM with both fixed (i.e., *time* [E1–E8]) and random (i.e., *participant*) factors were assessed. The model fit was determined using Akaike's information criterion (AIC) with the most suitable for all variables deemed the first order auto-regressive (AR-1) repeated covariance structure for the repeated measures. Main effects for time were identified *post hoc* using Fisher's LSD with 95% confidence intervals (CI) for the difference reported where significance was detected. Unless otherwise specified, data are expressed as mean ± SE and were analysed using SPSS version 26.0 (SPSS Inc., Chicago, IL, USA). Alpha was accepted as $p \leq .05$ prior to analyses. Pearson's correlation coefficient was used to assess the strength of association between PlayerLoad™ variables and lower-limb excitation and torque responses, with correlations described as small (0.1–0.29), moderate (0.3–0.49) or strong (0.5–0.7) (Hopkins, 2000).

5.3 RESULTS

Significant reductions were identified for normalised EMG_{RF} between E8 (88 ± 4%; 95% CI = 78.9 to 96.2%) versus E1 (−12%; 100 ± 4%; 95% CI = 92 to 102%; 95% CI for diff = −24 to −1 %; *p* = .037), E2 (−11%; 99 ± 4%; 95% CI = 91 to 108%; 95% CI for diff = −23 to −2 %; *p* = .047) and E4 (−12%; 100 ± 4%; 95% CI = 92 to 108%; 95% CI for diff = −23 to −1 %; *p* = .030). No significant time effects were observed for EMG_{BF} (*p* = .73).

As illustrated in Figure 5.2A, a 10.5% reduction in peak torque was observed for $eccKF_{180}$ from pre- (162.3 ± 9.0 Nm; 95% CI = 143.2 to 181.3 Nm) to post-exercise (145.2 ± 9.0 Nm; 95% CI = 126.1 to 164.3 Nm; 95% CI for diff = −33.9 to −0.8 Nm; *p* = .042). Peak torque was significantly reduced by 7.5% for $eccKF_{270}$ from pre- (159.0 ± 9.0 Nm; 95% CI = 139.4 to 178.6 Nm) to post-exercise (147.2 ± 9.0 Nm; 95% CI = 127.6 to 166.7 Nm; 95% CI for diff = −22.4 to −1.3 Nm; *p* = .034), and by 7.7% for $eccKF_{60}$ from pre- (159.5 ± 7.9 Nm; 95% CI = 142.4 to 176.6 Nm) to post-exercise (147.2 ± 7.9 Nm; 95% CI = 142.4 to 176.6 Nm; 95% CI for diff = −21.7 to −3.0 Nm; *p* = .018; Figure 5.2B and 5.2C). No differences were observed for the conKE data recorded pre- (180 deg·s^{-1} = 150.8 ± 7.7 Nm; 270 deg·s^{-1} = 116.8 ± 5.6 Nm; 60 deg·s^{-1} = 193.7 ± 11.0 Nm) when compared to post-exercise (180 deg·s^{-1} = 153.0 ± 7.8 Nm; *p* = 0.441; 270 deg·s^{-1} = 114.8 ± 5.6 Nm; *p* = .493; 60 deg·s^{-1} = 183.3 ± 11.0 Nm; *p* = .062). As outlined in Table 5.1, significant main effects for time were identified for PL_{Total} (p < .010), PL_V (p = .038) and $PL_{A\text{-}P}$ (p < .010), though no time point differences were detected for $PL_{M\text{-}L}$ (p = .094). Mean (± SD) percentage contributions of PL_{Total} were 53 ± 3 % (PL_V), 24 ± 3 % ($PL_{A\text{-}L}$) and 23 ± 2 % ($PL_{M\text{-}L}$) throughout the 120 min simulation.

As indicated in Table 5.2, a large and inverse correlation was observed between EMG_{RF} and PL_{Total} (r = -0.50, $p \leq 0.01$). Medium inverse associations were also established for EMG_{RF} and PL_V (-0.43) and $PL_{A\text{-}P}$ (-0.47, both $p \leq 0.01$). A small inverse correlation was identified for EMG_{RF} and $PL_{M\text{-}L}$ (-0.29, $p \leq 0.01$). No significant correlations were found between any other variables.

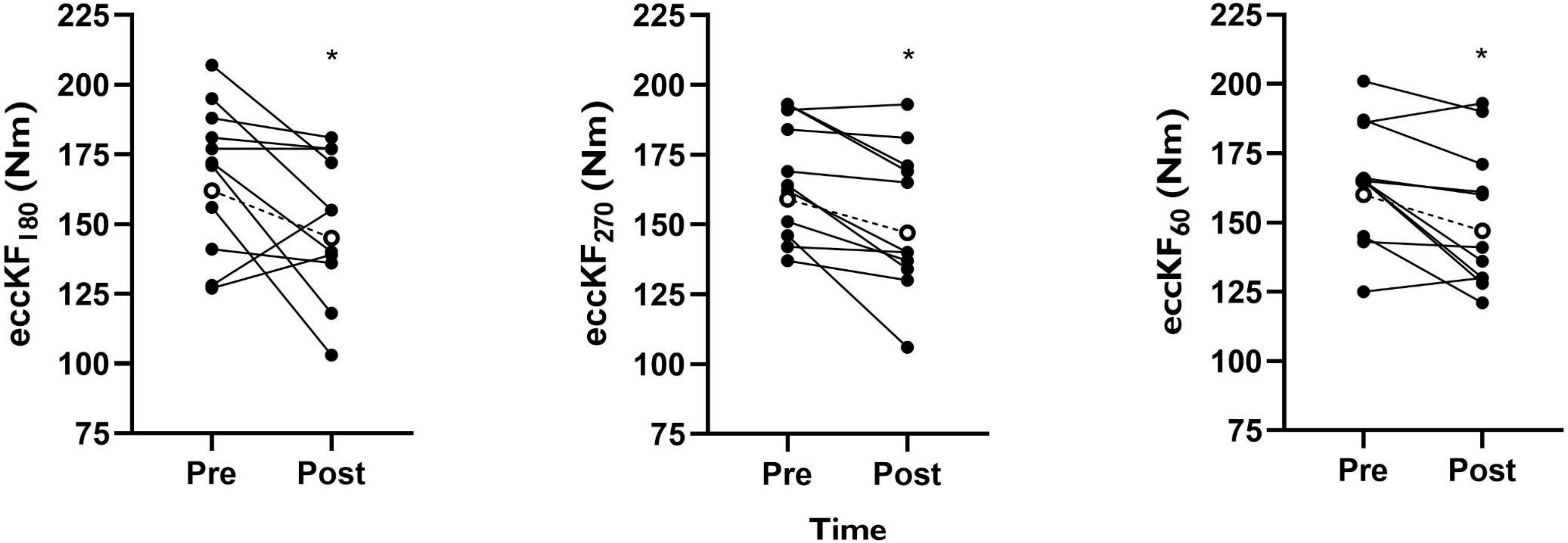

Figure 5.2. Individual eccKF peak torque values across angular velocities of 180 (A), 270 (B) and 60 deg·s^{-1} (C). * indicates significant difference from pre- to post-exercise. Dash lines with open circles represent mean eccKF response

Table 5.1. Muscle excitation and PlayerLoad™ responses throughout the 120 min soccer simulation (mean ± SE)

	Time							
Variable	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**
EMG_{RF} (%)	100 ± 4	99 ± 4	97 ± 4	100 ± 4	95 ± 4	93 ± 4	95 ± 4	87 ± 4 95% CI = −24 to −1[a]; −23 to −2[b]; −23 to −1[d]
EMG_{BF} (%)	100 ± 3	100 ± 3	102 ± 3	104 ± 3	103 ± 3	99 ± 4	101 ± 3	103 ± 4
PL_{Total} (a.u)	218 ± 7	221 ± 7 95% CI = 1 to 7[a]	221 ± 7	226 ± 7 95% CI = 2 to 13[a]; 1 to 8[c]	230 ± 7 95% CI = 5 to 18[a]; 3 to 14[b]; 4 to 13[c]; 1 to 7[d]	231 ± 7 95% CI = 6 to 20 [a]; 3 to 16 [b]; 5 to 16 [c]; 1 to 10 [d]	234 ± 7 95% CI = 3 to 13[a]; 3 to 12[b]; 4 to 12[c]; 2 to 9[d]; 1 to 6[e]; 1 to 4[f]	236 ±7 95% CI = 3 to 14[a]; 2 to 12[b]; 3 to 12[c]; 1 to 9[d]
PL_V (a.u)	115 ± 5	116 ± 5	116 ± 5	119 ± 5 95% CI = 1 to 5[c]	121 ± 5 95% CI = 1 to 9[a]; 1 to 8[b]; 2 to 7[c]	121 ± 5 95% CI = 1 to 11[a]; 1 to 9[b]; 1 to 9[c]	124 ± 5 95% CI = 3 to 14[a]; 2 to 12[b]; 4 to 12[c]; 1 to 9[d]; 1 to 6[e]; 1 to 4[f]	124 ± 5 95% CI = 3 to 14[a]; 2 to 12[b]; 3 to 12[c]; 1 to 9[d]
$PL_{A\text{-}P}$ (a.u)	52 ± 3	54 ± 3 95% CI = 1 to 3[a]	54 ± 3 95% CI = 1 to 3[a]	54 ± 3 95% CI = 1 to 4[a]	56 ± 3 95% CI = 2 to 5[a]; 1 to 4[b]; 1 to 4[c]; 1 to 3[d]	57 ± 3 95% CI = 2 to 6[a]; 1 to 4[b]; 1 to 4[c]; 1 to 3[d]	57 ± 3 95% CI = 3 to 7[a]; 1 to 5[b]; 2 to 5[c]; 1 to 4[d]	58 ± 3 95% CI = 4 to 8[a]; 2 to 6[b]; 3 to 6[c]; 2 to 5[d]; 1 to 3[e]; 1 to 3[f]
$PL_{M\text{-}L}$ (a.u)	50 ± 3	51 ± 3	51 ± 3	52 ± 3	53 ± 3	53 ± 3	54 ± 3	54 ± 3

Note. EMG_{RF} = Mean electromyography for rectus femoris; EMG_{BF} = Mean electromyography for bicep femoris; PL_{Total} = PlayerLoad total; PL_V = PlayerLoad vertical; $PL_{A\text{-}P}$ = PlayerLoad anterior-posterior; $PL_{M\text{-}L}$ = PlayerLoad medial-lateral; CI 95% = 95% confidence intervals for the difference.
[a–g] Indicates significant differences from E1–E7 ($p \le .05$), respectively.

Table 5.2. Correlational values between PlayerLoad™ and lower-limb excitation and peak torque responses

Variable	PL_{Total}	PL_{V}	$PL_{A\text{-}P}$	$PL_{M\text{-}L}$	$PL_{V\%}$	$PL_{A\text{-}P\%}$	$PL_{M\text{-}L\%}$
EMG_{RF}	-0.50**	-0.43**	-0.47**	-0.26**	0.01	-0.04	0.06
EMG_{RF}	-0.18	-0.10	-0.02	-0.13	-0.11	-0.10	-0.02
$conKE_{180}$	-0.21	-0.06	-0.20	-0.27	0.15	-0.05	0.17
$conKE_{270}$	-0.27	-0.11	-0.29	-0.28	0.16	-0.09	-0.03
$conKE_{60}$	0.04	0.10	-0.07	0.01	0.09	-0.09	-0.03
$eccKF_{180}$	0.15	0.06	0.14	0.19	-0.16	0.08	0.12
$eccKF_{270}$	0.16	0.11	0.10	0.15	-0.07	0.02	0.08
$eccKF_{60}$	0.15	-0.02	0.28	0.19	-0.32	0.21	0.16

**Indicates significant correlation ($p \geq 0.01$)

5.4 DISCUSSION

The main purpose of this study was to assess thigh musculature excitation and peak torque in response to 120 min of soccer-specific exercise. In line with the study hypotheses, an ET period elicited a reduction in EMG_{RF} and decreased eccKF peak torque from pre-to-post 120 min of soccer-specific exercise. Increments in PlayerLoad™ were identified as a function of exercise duration which was further increased during ET. However, no changes in indices of conKE peak torque were observed, nor did the degree of muscle excitation change throughout the exercise simulation in the biceps femoris.

Normalised EMG_{RF} amplitudes were reduced during ET, though excitation deficits were not associated with significant impairments in conKE following the 120-min simulation. These results are consistent with previous findings demonstrating that patterns of potentiated knee-extensor voluntary activation do not reflect deficits in maximal knee extensor force capacity following ET (Goodall et al., 2017). Therefore, it is considered likely that the knee extensor fatigue experienced during ET occurs centrally along the pathway and could be linked to a reduced neural drive and/or excitation contraction coupling as opposed to within-muscle contractile failure and/or substrate depletion. Duration dependent central fatigue development has also been observed in response to varying exercise modalities (Place et al., 2007; Thomas et al., 2015). However, the reduction in muscle excitation during high velocity sprinting in response to an additional ET period is a novel finding and implies that central fatigue (indicated through reduced surface EMG signals) may progressively become a more prominent limiting factor in response to an increased exercise duration.

The reduction in EMG_{RF} amplitude during a fixed output soccer-specific treadmill simulation is in line with previous findings (Rahnama et al., 2006). However, the lack of change in EMG_{BF} amplitude across 120 min in the present study was an unexpected finding and contradicts previous work reporting reductions in EMG_{BF} following a soccer-specific treadmill simulation (Rahnama et al., 2006). The conflicting results might be partly attributed to differences in the soccer simulation protocol and EMG measurements. Rahnama et al. (2006) used a soccer simulation which involves a different activity profile (i.e., a disproportionate amount of high-speed running) to the present study. They also measured the mean RMS value of EMG amplitudes in a separate protocol at three time points (pre, HT and post simulation) as opposed to during the protocol itself, potentially allowing aspects of central fatigue development to dissipate. The lack of EMG amplitude inhibition for EMG_{BF}, despite the reduction in EMG_{RF} in the current investigation implies that neural fatigue may occur sooner in the quadriceps than in the hamstrings during soccer-specific exercise. This is perhaps due to the repetitive braking forces incurred during rapid decelerations, for which the quadriceps are a primary muscle group (Hewit et al., 2011). As a result, it is possible that if the hamstrings were incapable of performing these functions, injury risk may have been increased during rapid deceleration movements.

The lack of change for EMG_{BF}, despite eccKF strength reductions following ET implies the strength capacity of the hamstrings were impaired, but still maintained a similar level of muscular excitation from E1 (100 ± 3%) to E8 (103 ± 4%). Having to maintain activation of the biceps femoris in spite of a reduced strength capacity, may be as a result of the fixed task requirements associated with the current standardised treadmill-based soccer-specific protocol. Conversely, it has previously been purported that impairments in contractile properties of the muscle require an elevated neural drive to maintain a constant running velocity, which are reflected with larger EMG amplitudes within working muscles (Pincivero et al., 2000). However, the torque reductions observed are possibly explained by a protective mechanism which acts to regulate extracellular damage by enforcing a temporary energy restriction to limit the recruitment of muscle fibres. This may be imposed because muscle fibres are unable to disregard cerebral and neural commands which control the recruitment of motor units and subsequent muscle contraction (Baird et al., 2012). Another plausible explanation may be that musculature that play a role in flexing the knee were measured as a unit, and as such, the maintenance of excitation in the biceps femoris may suggest that the observed changes in peak torque may be due to impairments in other such muscles — semitendinosus, semimembranosus, sartorius, gracilis, popliteus and gastrocnemius — that contribute to knee flexion. It is also possible that due the biceps femoris causing external rotation of the knee joint (Opar et al., 2012), the lack of CoD movements involved with treadmill running, may have resulted in a conservative response when compared to match-play in the sense that the biceps femoris may be stressed to a greater extent from CoD tasks.

A reduction in eccKF torque production was observed in the present study, irrespective of the isokinetic testing speed. However, conKE appear to maintain their torque capacity from pre- to post-120 min, despite a reduction in muscle excitation. Considering the standardised nature of the protocol, other musculature must compensate for the reduced neural drive to the quadriceps to maintain the propulsion needed to perform the exercise protocol. Therefore, it is possible that the reductions in eccKF peak torque are due to an inhibited quadriceps excitation and subsequent changes to how other musculature operate. It is also likely that differences in muscle composition can explain the disparity in peak torque maintenance between muscles. For instance, while the precise anatomical properties that predispose hamstrings to peripherally derived measures of reduced strength are unclear, it has been purported that fibre type distribution and muscle architecture are factors that may contribute (Opar et al., 2012). It should also be considered that symptoms of muscle damage and soreness are exacerbated in response to eccentric versus concentric modes of exercise (Peake et al., 2017). Hamstring strains typically occur when the lengthening demand of the muscle exceeds the tissue strength limits, with fatigued muscles able to absorb less energy before failure versus unfatigued muscles (Coratella et al., 2015; Greig, 2008). Eccentric strength exercises reportedly shift the optimum length-tension curve (i.e., towards greater lengths/joint angles), thus reducing hamstring strain injuries at extended joint positions (Brughelli & Cronin, 2008). A 12-week Nordic hamstring protocol delivered bi-weekly before training, resulted in a greater degree of improvement at extended muscle lengths versus post-training (Lovell et al., 2018). As such, implementing such preventative exercises within training programmes appears warranted. Practitioners should develop the eccentric component of the hamstrings to increase player resistance to fatigue-induced torque deficits and increase the muscle length at which eccentric hamstring torque development is attained to reduce hamstring injury susceptibility during the ET period.

The magnitude of the reduction in eccKF torque generation from pre- to post-exercise at 270 and 60 $deg \cdot s^{-1}$ were similar with that of previous work using corresponding measures at 300 and 60 $deg \cdot s^{-1}$ following 90 min of a treadmill simulation (Page et al., 2019). The deficit in eccKF torque between pre- and post-exercise suggests that soccer players are unable to attain peak torque of the eccKF musculature following 120 min of soccer-specific activity. However, as evident in Figure 5.2, large inter-individual variability was present for eccKF with changes ranging from −34% to +21% (depending on the isokinetic speed) between pre- and post-exercise. This suggests that muscle contractile fatigue mechanisms are highly dependant on the individual and thus, torque deficits should be interpreted on an individual level.

Reductions in muscle torque generation and subsequent compensatory adjustments in gait can manifest as changes in movement patterns (Jonkers et al., 2003). Therefore, the compromised capacity of the players in this study to maintain eccKF peak torque may partially elucidate the increase in $PL_{A\text{-}P}$ postural sway. Specifically, the mechanism likely involved an impaired ability for the hamstrings to maintain hip extension (i.e., an upright trunk posture), coupled with a potential antagonistic dominance of the quadriceps musculature in flexing the hip. It is well-established that the hamstrings are most susceptible to injury during the late swing phase of sprinting due to lengthening across both hip and knee joints (Chumanov et al., 2012), and are possibly in a comprised state following 120 min of soccer-specific exercise. Therefore, it may be pertinent for players to employ pacing strategies to reduce the impact of fatigue-induced reductions in eccKF strength during matches that proceed to ET. However, players were unable to ‘self-pace’ during the current study (i.e., the treadmill dictated the activity profile), thus, a reduced physical capacity may have instead manifested through increases in PlayerLoad™ metrics. Furthermore, the ~7.5–10.5% deficit in knee flexor torque production identified pre- to post-exercise supports an increased hamstring injury propensity and a compromised joint stability (Page et al., 2019), elicited by 120 min of exercise. Therefore, although speculative, players not conditioned to manage the additional demands of ET, may be at an increased susceptibility to suffer an acute musculotendinous rupture during this additional 30 min period.

Similar to the reduced physical performance capacity observed in the latter stages of 120-min matches (Peñas et al., 2015; Russell et al., 2015b), it has been demonstrated that PL_{Total} increases during ET when compared to a number of the preceding fixed bouts of treadmill-based simulated soccer-specific exercise (Chapter 4). The changes in PlayerLoad™ (PL_{Total}, PL_{V}, $PL_{A\text{-}P}$ and $PL_{M\text{-}L}$) appear to inversely correspond with muscle excitation responses of the muscle excitation of the biceps femoris (EMG_{RF}). The size of the correlations ranged from small (-0.29) to large (-0.50) and statistical significance was reached on a level ≤ 0.01. Therefore, these data provide an initial step towards providing evidence that suggests PlayerLoad™ metrics are somewhat reflective of EMG lower-limb thigh musculature changes. However, before these metrics can be used to infer changes in lower-limb fatigue, prospective validation of PlayerLoad™ metrics is required that focus intently and establish the extent to which changing planar contributions reflect EMG lower-limb patterns during both treadmill and free-running soccer simulations.

While this study offers novel insight into muscle excitation and torque production throughout 120 min of soccer exercise, there are some methodological limitations present within the current research. Firstly, the absence of additional isokinetic peak torque measures for the thigh musculature (i.e., eccentric knee extensors and concentric knee flexors) may be considered a limitation, especially given the role of the knee extensors during eccentric knee flexion upon ground contact (Paquette et al., 2017). Reductions in strength of the eccentric knee extensors could lead to kicking related injuries and therefore is an important future avenue of research. While EMG was measured at 15-min time intervals throughout the simulation, peak torque was only measured pre and post the 120-min protocol. This could be deemed a limitation, however, additional measures on the isokinetic dynamometer at 15-min intervals would have invalidated the soccer-specific fatigue response and, as such, was considered inappropriate for this study. Furthermore, although participants covered distances (16.26 km) and performed the number of sprints (n = 56) comparable with an actual 120 min match (Russell et al., 2015b; Winder et al., 2018), the pre-arranged nature and lack of kicking, jumping and tackling actions involved with simulations will inevitably impact peripheral and central patterns of fatigue. Notwithstanding the considerable experimental control of the current research, its lack of ecological validity yields difficulty when extrapolating the data to match-play scenarios considering the number of contextual variables that influence soccer match performance (Castellano et al., 2011).

5.5 CONSCLUSIONS

To summarise, thigh musculature excitation, peak torque production, and PlayerLoad™ were investigated in response to 120 min of soccer-specific activity. These novel data suggest that muscle excitation of the rectus femoris was reduced during ET, though no notable change was evident in the biceps femoris throughout 120 min of soccer-specific activity. The eccentric torque generating capability of the knee flexors was reduced post 120 min compared with baseline assessments. Increases in PlayerLoad™ were evident as a function of exercise duration, which was further increased during the additional period of ET. It is recommended that exercises are implemented within the weekly training schedule to develop resistance to fatigue-induced knee flexor torque deficits to limit injury risk during matches that progress to the ET period. Carefully considered interventions should also be orchestrated following ET matches to promote recovery and enhance physical performance in subsequent matches. To inform these interventions and gather an understanding of the recovery practices that are currently employed in the field following ET, empirical observations must be carried out on professional soccer practitioners.

6.0 RECOVERY FOLLOWING THE EXTRA-TIME PERIOD OF SOCCER: PRACTITIONER PERSPECTIVES AND APPLIED PRACTICES

Publication arising from this chapter:

Field, A., Corr, L., Thompson, C., Gonzalez Lucena, J. C., Sarmento, H., Naughton, R., Brownlee, T., Haines, M., Page, R., Harper, L. (2022). Recovery following the extra-time period of soccer: Practitioner perspectives and applied practices. Biology of Sport, 39(1): 171–179.

Author contributions

Adam Field wrote the first draft of the manuscript. Adam Field and Liam Corr analysed they survey data. All authors disseminated the survey. All authors reviewed the manuscript at various stages throughout the editing process. All authors read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

6.0.1 ABSTRACT

Research has demonstrated that the ET period of soccer negatively impacts recovery. However, it is not known to what extent recovery practices are being adapted by practitioners following ET and where gaps exist between research and practice. Therefore, this study explored soccer practitioner perceptions of recovery practices following ET matches. A total of 72 practitioners across different levels of soccer and several countries completed a bespoke online survey. Inductive content analysis of the responses identified five higher-order themes: 'conditioning', 'player monitoring', 'recovery practices', 'training', 'and 'future research directions'. Mixed responses were received in relation to whether practitioners condition players in preparation for ET, though 72% allowed players to return to training based on fatigue markers following this additional 30-min period. Sixty-three (88%) practitioners believed that ET delays the time-course of recovery, with 82% highlighting that practices should be adapted following ET compared with a typical 90-min match. Forty-nine practitioners (68%) reduce training loads and intensities up to 48 hr post ET matches, though training mostly recommences as 'normal' at 72 hr. Sixty-three (88%) practitioners believed that more research should be conducted on recovery following ET, with 'tracking players physiological and physical responses', 'nutritional interventions to accelerate recovery' and 'changes in acute injury-risk' being the three areas of research that practitioners ranked as most important. These data suggest practitioners and coaches adjust recovery practices following ET matches compared to 90 min. Further research on the efficacy of recovery strategies following ET matches is required to inform applied practice.

6.1 INTRODUCTION

Soccer matches are typically contested over 90 min, though when scores are tied, in the knockout phase of some major competitions (e.g., FIFA World Cup and UEFA Champions League) matches progress into an additional 30 min period of ET. Notably, 41% of knockout phase matches proceeded to ET at the 2014 and 2018 FIFA World Cup competitions (Kołodziejczyk et al., 2021). Subsequently, since 2014 there has been a growth in research on ET (for a review see Chapter 2). Simulated and actual match-play observations have shown that ET elicits additional central fatigue (Goodall et al., 2017) and reduces physical performance capacity (Russell et al., 2015b). Evidence suggests that 120 min of match-play also has a negative impact on fatigue and recovery, including increases in blood creatine kinase concentrations (indicative of muscle damage), as well as reductions in jump height (Russell et al., 2015b) and wellness scores compared to 90-min matches (Winder et al., 2018).

Recovery strategies are key to alleviate the debilitating effects of fatigue (Nédélec et al., 2012). However, with players competing in up to 60 games per season and exposed to fixture congested schedules (Julian et al., 2020a), insufficient between-match recovery periods may impede a player's ability to perform optimally in consecutive matches (Nédélec et al., 2012; Page et al., 2019). Extra-time matches are often competed amid fixture congested schedules across a season and during tournaments (Julian et al., 2020a). Therefore, the delay in returning players to cellular homeostasis and peak functional capacity following ET matches may have harmful implications for recovery and subsequent performance. In contemporary elite soccer, practitioners and coaches are responsible for implementing evidence-informed strategies designed to accelerate recovery (Carling et al., 2015). However, recovery in response to ET is under-researched, and as such, practitioners are faced with challenges concerning whether to remain with common (90min) modalities or adapt practices to aid recovery following ET matches. Furthermore, to understand how professional soccer practitioners manage recovery following the peripheral and central fatigue identified in Chapter 5, it might be beneficial to survey professional soccer practitioners' views and perceptions. This study was also informed by the systematic review with there presently existing a lack of research assessing recovery approaches in the field after 120 min matches.

Survey data from professional soccer practitioners suggests that ET influences 89% of the respondents' recovery practices and that recovery modalities are considered an important area of future research (Harper et al., 2016c). However, the survey in this research was primarily focused on performance and nutritional interventions during ET, with little focus on recovery. Therefore, empirical research should examine the current applied practices in relation to recovery and ET. Furthermore, it is challenging to precisely measure how research findings and recommendations are applied by sports science practitioners and coaches working in the field. As such, collecting practitioner survey data is a useful method to explore perceptions and practices employed in an attempt to 'bridge the gap' between evidence-based research and applied practice in soccer (Harper & McCunn, 2017).

Researchers have been criticised for failing to develop and deliver new knowledge that can easily be translated into a real-word setting (Bishop, 2008). One such approach to enhancing the translational potential of research is through qualitative research design (Harper & McCunn, 2017). Previous research in professional soccer has adopted the use of surveys to investigate training load and player monitoring (Weston, 2018), injury prevention strategies in youth soccer (Read et al., 2018), the practices of substitutes (Hills et al., 2020) and feedback of GPS training data (Nosek et al., 2021). Indeed, incorporating open-ended questions within the survey design, thus allowing practitioners to expand on a given response, may facilitate critical understanding of the difficulties experienced and barriers involved with operating in an applied environment (Harper et al., 2016c). However, there is still currently adjudged to be a significant 'science to practice' disconnect in soccer (Buckthorpe et al., 2019). Therefore, implementing an evidence-led approach may highlight existing gaps whilst yielding study designs of increased ecological validity, thus ensuring apposite experiments are conducted to assist with an increased adoption in a practical setting (Dunlop et al., 2019).

Given the paucity of research exploring approaches to recovery following ET matches, the purpose of this study was to explore practitioners' and coaches' perceptions and practices with reference to ET and recovery. This research approach was undertaken with the intention of retrieving valuable insights into contemporary practice, contextualising potentially existing gaps and guiding future research designs.

6.2 METHODS

6.2.1 Participants

Upon receiving institutional ethical approval, 208 soccer club or federation representatives were contacted between January 2020 and June 2020 (Table 6.1). Each recipient received a short description of the research, a web-link to the survey as well as a password required to access the survey. Representatives were encouraged to share the survey with the most appropriate practitioner/coach within their team with responsibility for implementing recovery practices. Upon obtaining access, the procedures involved with completion were outlined, and informed consent and confirmation that respondents were ≥18 years of age was required to progress to the survey questions. Practitioners were asked to provide information relating to their job role, competitive level, as well as the tier and country their team competed in, though anonymity was otherwise maintained. International practitioners were asked to disclose the

Table 6.1. Details of the competitive league and response rate of the invited clubs

League (National tier)	**Responses** (Invited/Responded/Included)
English Premier League (1st tier)	17/9/8
English Championship (2nd tier)	21/10/7
English League One (3rd tier)	21/11/9
English League Two (4th tier)	18/13/10
English National League (5th tier)	17/3/1
English National League North/South (6th tier)	17/10/6
Scottish Premiership (1st tier)	5/2/2
League of Ireland Premier Division (1st tier)	2/1/1
Portuguese Premeira Liga (1st tier)	6/4/4
Portuguese LigaPro (2nd tier)	4/1/1
Portuguese Terceira Liga (3rd tier)	1/1/1
Campeonato de Portugal Serie A (4th tier)	1/1/1
Italian Serie A (1st tier)	4/2/2
French Ligue 1 (1st tier)	3/1/1
Super League Greece (1st tier)	1/1/1
Hungary OTP Bank Liga (1st tier)	1/1/1
Spain Segunda División B (3rd tier)	1/1/1
Qatari Stars League (1st tier)	4/2/2
Taiwan Football Premier League (1st tier)	1/1/1
Australian A League (1st tier)	4/2/2
Other leagues	45/2/0
International associations	
Union of European Football Associations	7/4/4
Asian Football Confederation	5/4/4
Confederation of African Football	1/1/1
Confederation of North, Central American and Caribbean Association Football	1/1/1
Total	**Invited: 208, Responded: 87 Included: 72**

continent in which their team were situated. If the survey was not fully completed upon terminating survey uptake, the participants responses were excluded from analyses.

6.2.2 Survey development

The survey was constructed using Qualtrics.XM online software (Utah, USA; https://www.qualtrics.com/uk/). Two professional practitioners and two semi-professional coaches, as well as a researcher with previous experience of constructing surveys of this nature, piloted and reviewed the questions to check usability and face validity. Several alterations were then carried out: three questions were rephrased, or a description added to provide clarity, three questions were amended to ensure practitioner relatability, and the wording of one question was adjusted as it was potentially ‘leading’.

The final version of the survey comprised relevant background information, followed by an informed consent section and a page whereby practitioners were required to enter a unique I.D which could later be used to withdraw responses. The survey contained 14 main questions and five sub-items across 12 pages, each taking either a scaled, rank, multiple-choice or open-ended format allowing practitioners to expand on four individual questions. Respondents were asked to consider their conditioning practices, monitoring procedures used to inform returning players to training, recovery strategies and future research recommendations specific to ET matches compared with the approaches ordinarily taken in relation to a 90-min match (see Appendix 8 for the survey questions).

All survey items included a ‘forced-response’ feature (i.e., a response was required to progress) and adaptive questioning was used in the form of ‘skip logics’ to avoid interrupting survey flow; ensuring that solely relevant items were addressed. The survey was originally developed in English and later translated (using the translation function of Qualtrics.XM and thereafter cross-checked and edited by native speakers) into Portuguese and Spanish.

6.2.3 Survey analyses

The study design is of a cross-sectional and descriptive nature and as such, the data is presented in a descriptive manner. Upon cessation of survey data uptake, raw data were exported to Microsoft Excel (Microsoft Corp., Redmond, WA, USA). Native speakers, proficient in translation checked open responses to ensure content accuracy. The checklist for reporting results of internet e-surveys (CHERRIES) was adhered to for both survey design and analyses (Eysenbach, 2012).

For Likert-scale questions, unipolar 5-point and bipolar 7-point scale questions were used, asking practitioners to indicate their perceived level of importance or extent of agreement. All points were labelled with qualitative anchors for importance (i.e., ‘not at all important’ [1], ‘slightly important’ [2], ‘moderately important’ [3], ‘important’ [4], and ‘very important’ [5]) and agreement (i.e., ‘very strongly agree’: 3, ‘strongly agree’: 2, ‘agree’: 1 ‘neither agree nor disagree’: 0, ‘disagree’: -1, ‘strongly disagree’: -2, ‘very strongly disagree’: -3) (Batyrshin et al., 2017). Frequency analysis was used to determine the percentage of practitioners that endorsed each response (Hills et al., 2020). Other items involved participants ranking (from ‘1’ to ‘5’) their order of perceived importance from a list of available responses, with the accumulation of scores for each option used to determine the mean order of importance (i.e., the choice rated first was scored 5 points, second—4 points, third—3 points, fourth—2 points, and fifth—1 point) (Harper et al., 2016c).

In order to facilitate elaborative answers, open-ended questions were used to offer participants the opportunity to ‘explain’ the reasons underpinning certain responses. These qualitative responses were systematically arranged and read diligently by the lead researcher (AF) on several occasions to develop a deep sense of the content and context of the data (Harper et al., 2016c). Inductive content analysis, described as an analytical process conducted in the absence of pre-conceptions or pre-determined framework was used (Patton, 2014). Raw data were open coded and grouped into larger and more general dimensions in a higher order concept (Dunlop et al., 2019). This process was repeated until theoretical saturation was achieved (Fusch & Ness, 2015). The list of themes were discussed at each stage and validated independently by two researchers (AF and LDC) until a consensus was reached regarding data interpretation and theme credibility (Dunlop et al., 2019).

6.3 RESULTS

A total of 72 completed all questions and were included in analyses. Initially, 87 practitioners/coaches returned the survey, though as all questions were not completed, thus, a further 15 practitioners were omitted. These numbers represent a 42% survey return rate and a completion rate of 83%. Table 6.2 shows the role and level of employment for each practitioner. Five general dimensions emerged from the survey data including ‘conditioning’, ‘player monitoring’, ‘recovery practices, ‘training’ and ‘future research directions’.

Table 6.2. Practitioner roles and level of employment upon survey completion

	Level of current employment				
Practitioner and coach roles	**Prof**	**Int**	**Semi-pro**	**Academy**	**Total**
Science Staff	**28**	**5**	**4**	**4**	**41**
Sports scientist	10	1	3	2	17
Head of sports science	1	0	0	0	1
Head of science & medicine	8	2	0	0	10
Strength & conditioning coach	4	1	1	1	8
Head of fitness & conditioning	1	0	0	0	1
Nutritionist	4	0	0	0	4
Exercise physiologist	0	1	0	1	2
Medical Staff	**5**	**1**	**3**	**2**	**11**
Sport therapist/physiotherapist	4	0	3	2	9
Club Doctor	1	1	0	0	2
Coaching staff	**11**	**4**	**3**	**2**	**20**
Fitness coach	8	3	1	0	12
Head/assistant coach	3	0	2	2	7
Head of talent ID	0	1	0	0	1
Total	**44**	**10**	**10**	**8**	**72**

Prof = professional, Int = international, Semi-pro = semi-professional

6.3.1 Conditioning

When practitioners were asked if they '*condition players outside of peak periods to be able to cope with the demands of extra-time',* the most prevalent responses were 'no' (*n* = 35; 49%), 'yes' (*n* = 26; 36%) and 'sometimes' (*n* = 11; 15%), respectively. 'Infrequency' (e.g., 'extra-time is a rarely experienced event'), 'time' (e.g., 'time restrictions make player access difficult'), 'expectation that normal practice is sufficient' (e.g., 'training loads are usually geared at the normal game exposure which should indirectly condition them to face extra-time periods') and 'other appropriate methods' (e.g., 'verbal encouragement and substitution strategies') were identified as second-order themes. Conditioning work involved 'exceeding duration' (e.g., 'we conduct training matches comprising of 4 x 25 min halves'), 'within week preparation' (e.g., 'training load is increased approx. 4-5 days prior to extra time games'), and 'strength and conditioning practices' (e.g., 'structured injury prevention sessions are used to prepare for extra-time').

6.3.2 Player monitoring

The frequency with which practitioners 'track player fatigue markers following ET matches and return to training based on such feedback' is reported in Figure 6.1. Players were returned to training based on 'subjective assessments' (31%; e.g., 'fatigue scales', 'wellness questionnaires', 'conversations with the players'), 'physiological status' (20%; e.g., 'creatine kinase analysis', 'heart rate variability', 'hydration and saliva samples'), 'physical performance metrics' (49%; e.g., 'countermovement jump', 'peak power output (watt bike)', 'isometric hamstring test', 'GPS data'). Conversely, 'logistical constraints' (e.g., 'we would like to, but finances may not stretch to this', 'financial reasons, time restrictions lack of staff and equipment etc') was the overriding explanation for a lack of adaption to monitoring practices.

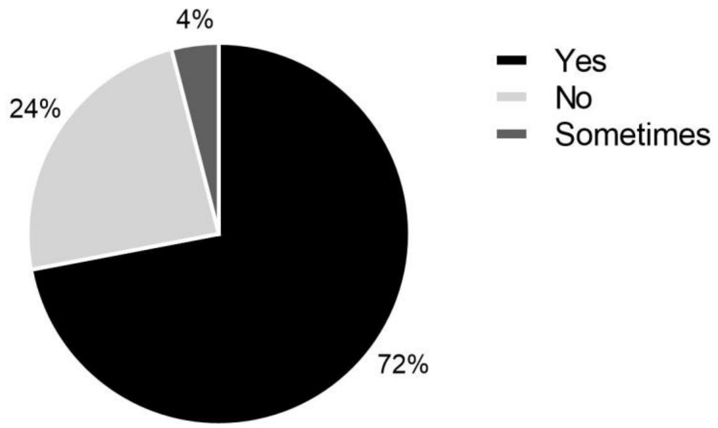

Figure 6.1. The proportion of practitioners that track player fatigue markers following ET matches.

6.3.3 Recovery practices

Practitioners were asked if they agreed with the following statement: *'extra-time further delays the time-course of recovery when compared to a 90 min match'* with no respondents 'very strongly disagreeing' (Figure 6.2). Most practitioners either 'very strongly agreed' (*n* = 10; 14%), 'strongly agreed; (*n* = 28; 39%) or 'agreed' (*n* = 21; 29%) that '*recovery practices should be adapted following an extra-time match versus a typical 90-minute match'*, while the remaining practitioners 'neither agreed nor disagreed' (*n* = 6; 8%) or 'disagreed' (*n* = 7; 10%) with this statement. Practitioners were asked to expand on why they held this viewpoint; with the second-order themes established for those in support of adapting recovery practices in response to ET provided in Table 6.3. Two second-order themes identified for those that remained neutral included 'individualised approaches' (e.g., 'recovery strategies are player-specific') and 'schedule dependent' (e.g., 'depends on the schedule and periodisation of the training week'). 'Lack of evidence' was highlighted as a second-order theme for those that 'disagreed' with adapting practice (e.g., 'I'm not convinced the literature is strong').

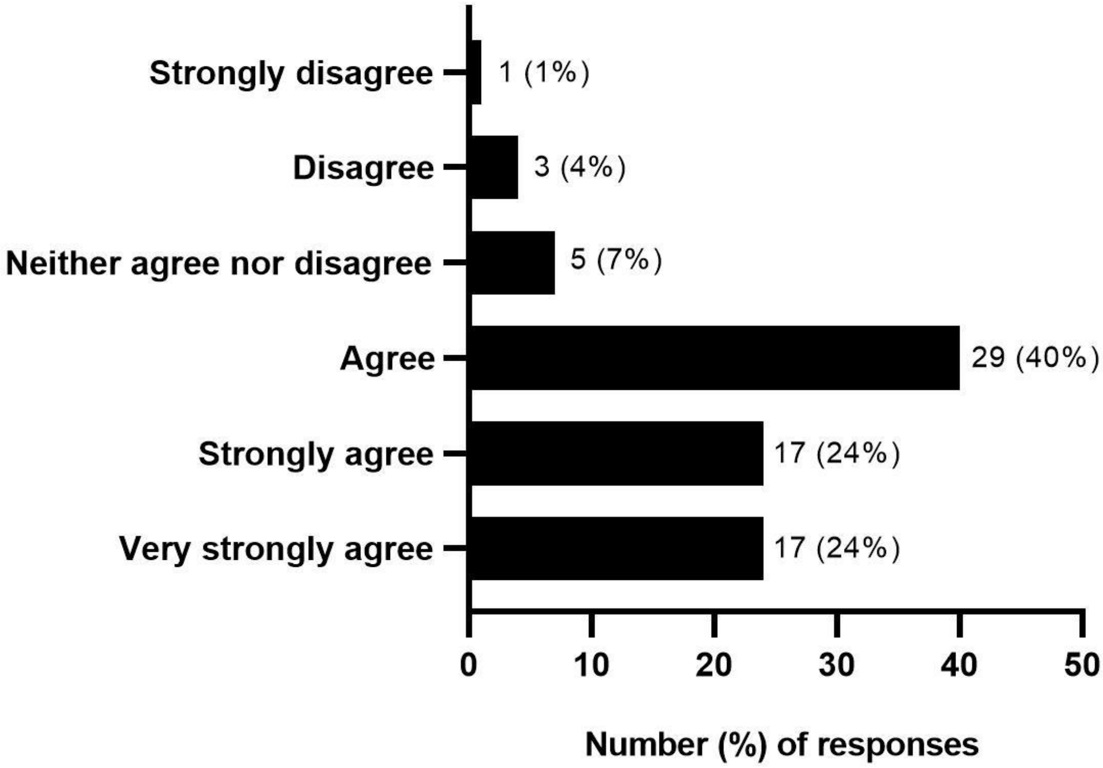

Figure 6.2. Practitioner extent of agreement to the statement regarding whether extra-time delays the time-course of recovery.

Table 6.3. Reasons provided for adapting recovery practices following matches that proceed to extra-time compared with typical 90 min matches

Second order theme	Supporting quotations
Physical stress	"increased muscle damage", "greater prospect of injury-risk", "excessive physical stress and loads are being placed on player", "extra stress on the skeletal system", "more micro trauma", "I believe players experience greater DOMS".
Physiological and metabolic demands	"added physiological demand", "a greater degree of oxidative stress", "further glycogen depletion", "more energy expended", "increased metabolic demand", "changes in substrate utilisation", "usually we find that individual internal markers are more adverse with extra-time".
Mental pressure	"players are not mentally able to cope", "we should also consider the emotional pressure associated with the extra time period", "there is likely an increased psychological demand due to increased pressure", "an extra-time match may impact psychometrics", "mental fatigue plays a critical part".
External load	"additional demands placed on the players (e.g., total distance, high-speed running and sprint distances)", "greater incidence of changes of direction and high-speed running", "increased external load than the typical experienced during normal 90 min games".
Exercise duration/volume	"Players are not conditioned for 120 minutes", "simply competing for an extended period of time", "taking into account the higher volume", "Depending on the duration of the match each individual player plays".

Cool down

Among practitioners that adapted their post-match cool downs, bespoke practice in the sense of 'duration' (e.g., 'prolonged cool down', 'more work around mobility') was employed.

Rest period

It was highlighted that 'additional rest' (e.g., 'we promote 1 day + 1/2 day off instead of the normal 1 day off', 'start the matchday +1 session later. Normally +1 to 2 hours') was given to players post ET matches which was largely based upon 'individual game-time' (e.g., 'depending on duration each individual player plays another day of recovery may be planned') and 'manager discretion' (e.g., 'possibly yes if the manager is happy with the result he will give extra days off to recover').

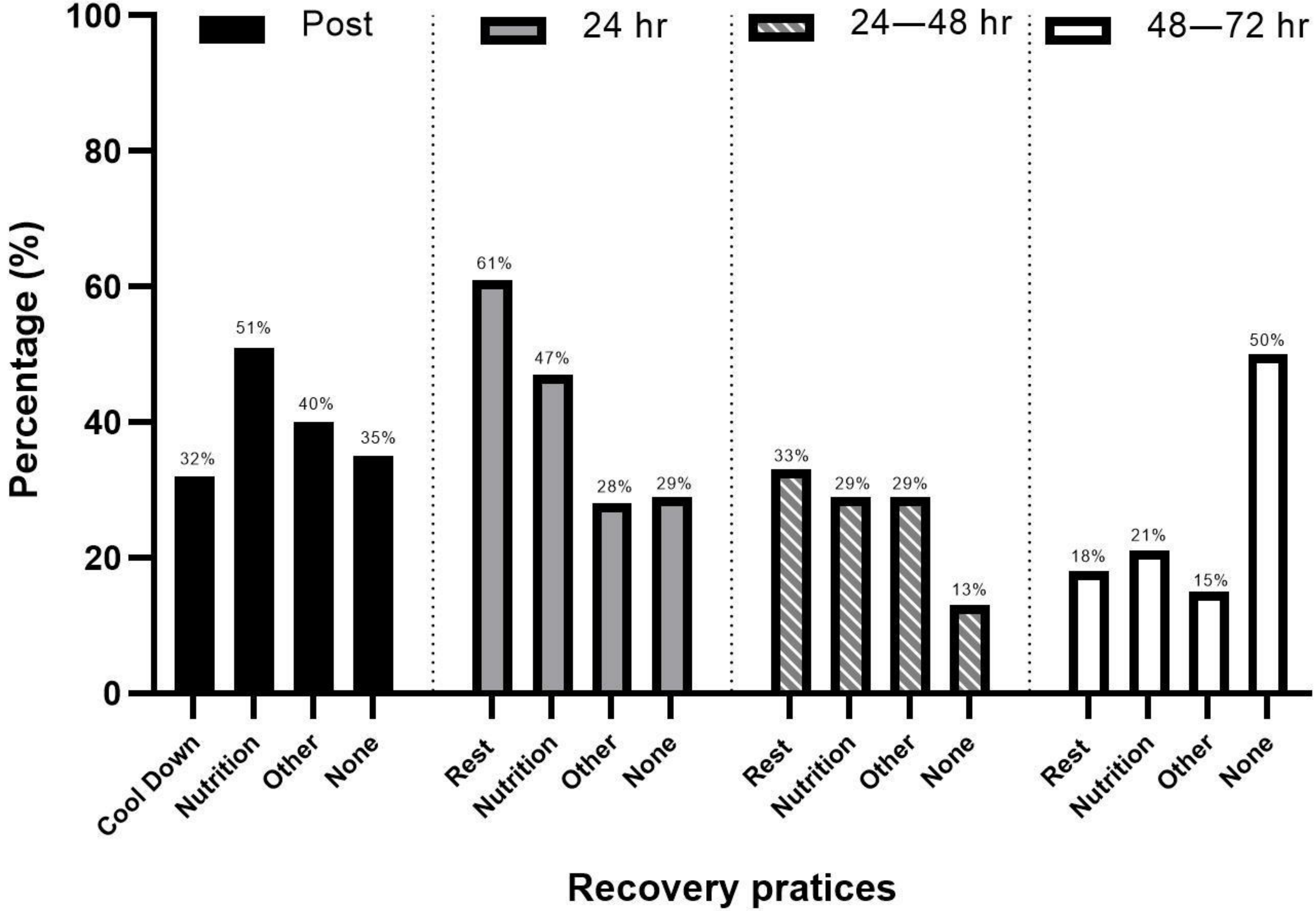

Figure 6.3. Percentage of practitioners that adapt specific recovery practices following matches that require extra-time compared with traditional 90-min matches.

Nutritional intake

Adapting nutritional intake immediately post-match mainly resides around modifying 'macronutrient intake' (80%; e.g., 'increase quantities of carb intake to replenish depleted glycogen stores, as well as increased protein intake to account for the additional tissue damage sustained'), 'hydration' (12%; e.g., 'electrolyte sachets for rehydration purposes'), 'supplementation' (5%; 'creatine', 'omega 3') and polyphenols (3%; e.g., 'beetroot/ tart cherry juice to help with inflammation'). Similar second-order themes were identified for the 24 and 24—48 hr post-match period with the addition of 'individualised nutritional provision' (e.g., 'depends on each player's physiological profile'), 'inter-disciplinary communication' (e.g., 'where possible we talk with the club chef'), and 'player education' (e.g., 'players aren't usually at the club but are advised to increase calorie intake'). A reduction in adaptation to nutritional practice was observed 48—72 hr post ET, with the 15 practitioners (21%) that persisted with modifying nutritional intake being largely 'schedule dependent' (e.g., 'periodisation to previous match and subsequent training/match schedule').

Additional specific recovery modalities

Non-nutritional recovery modalities identified as being adapted immediately post ET matches were mainly 'cryotherapy', 'massage', 'compression garments', and 'active recovery' with an increased emphasis on 'duration' (e.g., 'longer time spent in an ice bath') and 'intensity' (e.g., 'more intensive manual massage') of practice. Adjusting 'hydrotherapy' (e.g., 'cryotherapy', 'swimming', 'contrasting bathing') practices were prevalent among practitioners at 24, 24—48, and 48—72 hr post-match in response to 'individual preferences' (e.g., 'each individual player decides the modality').

No change to practice

Second-order themes that were identified as to why practice was not adjusted immediately post-match were 'time' (e.g., 'the delay to the end of the match puts us behind'), 'finance' (e.g., 'we are financially stretched with our usual practices'), and 'away matches' (e.g., 'often difficult to implement on away games'). For the 24—72 hr period following ET matches, 'recovery protocols deemed sufficient' (e.g., 'we feel we use the best protocols in this period irrespective of 90 or 120 min games'), 'player access' (e.g., 'do not have access to the players'), and 'squad rotation' (e.g., 'most competitions with extra time we would rotate the squad in order to compensate for the next game') were highlighted as key reasons that no change to practice was made.

6.3.4 Training

Practitioners were asked how important they believed it was to '*adapt training loads and intensities following an ET match'* versus conventional training practices. None of the practitioners considered adapting training loads 'not important', although six (8%) believed that doing so was 'slightly important'. 'Moderately important', 'important' and 'very important' received seven (10%), six (8%) and 53 (74%) responses, respectively. Adapting training intensities was of 'no importance' to one practitioner (1%), 'slight important' to four (6%), while a further 14 (19%) respondents attributed 'moderate importance' to this adaption. Nine (13%) believed it was 'important' to adapt intensities and the remaining 44 (61%) indicated this was 'very important'.

A total of 33 (46%), 49 (68%) and 28 (39%) out of the 72 practitioners adapted training loads and/or intensities at 24, 24—48 and 48—72 hr, respectively.

Training load/intensity adaption at 24 hr

Training loads and/or intensities were 'reduced' (e.g., 'volumes and intensities are decreased') by all 33 respondents at 24 hr with the primary motive underlying their decisions to taper training loads and intensities being associated with 'player health and well-being' (e.g., 'players health status takes priority', 'managed according to well-being').

Training load/intensity adaption at 24—48 hr

With regards to adapting training loads and/or intensities at 24—48 hr post 120 min matches, responses indicated that this was dependent on player 'physiological status' (e.g., 'dependent on recovery markers') and 'match completion' (e.g., 'reduce loads on players who completed the full game') as well as the 'preceding schedule' (e.g., 'dependent on accumulative output from the week') and 'upcoming schedule' (e.g., 'what competitions we have coming up'). 'Training variables' (e.g., 'manipulation of pitch sizes and drill times to restrict high-speed running, accelerations and decelerations') and 'training type' (e.g., 'players will have an extended off-feet recovery day (bike & pool)', 'tactical sessions used for starters') represented the most prevalent adaption to training.

Training load/intensity adaption 48—72 hr

The 28 practitioners that continued to adapt training at the 48—72 hr mark post ET matches outlined that though training loads and/or intensities were 'lesser than a normal training session; they were 'gradually built back up'. An 'individual approach' (e.g., 'adaptation according to the recovery status of each athlete') was reflective of the key second-order theme for this time period.

6.3.5 Future research directions

Sixty-three (88%) practitioners believed that '*further research should be conducted on the recovery response following the extra-time period'*, whilst the remaining nine (12%) did not believe that conducting research of this nature was required. The 63 practitioners were provided with a list of options ('tracking the physiological and physical response', 'nutritional interventions to accelerate recovery', 'changes in acute injury-risk', 'non-nutritional interventions to accelerate recovery' and 'other') and were asked to rank which they '*believed warranted further investigation following an extra-time match'* (Figure 6.4). When given the opportunity to indicate any 'other' areas aside from those provided, 'sleep' (e.g., 'sleep study'), 'cognitive aspect' (e.g., 'mental aspect of recovery and fatigue', 'cognitive readiness tests'), 'away match logistics' (e.g., 'effects of mode of travel and overnight stay vs travel on day') and 'subsequent performance' (e.g., 'performance in the following match'), were identified amongst the small number of practitioners (*n* = 6) that expanded on this option.

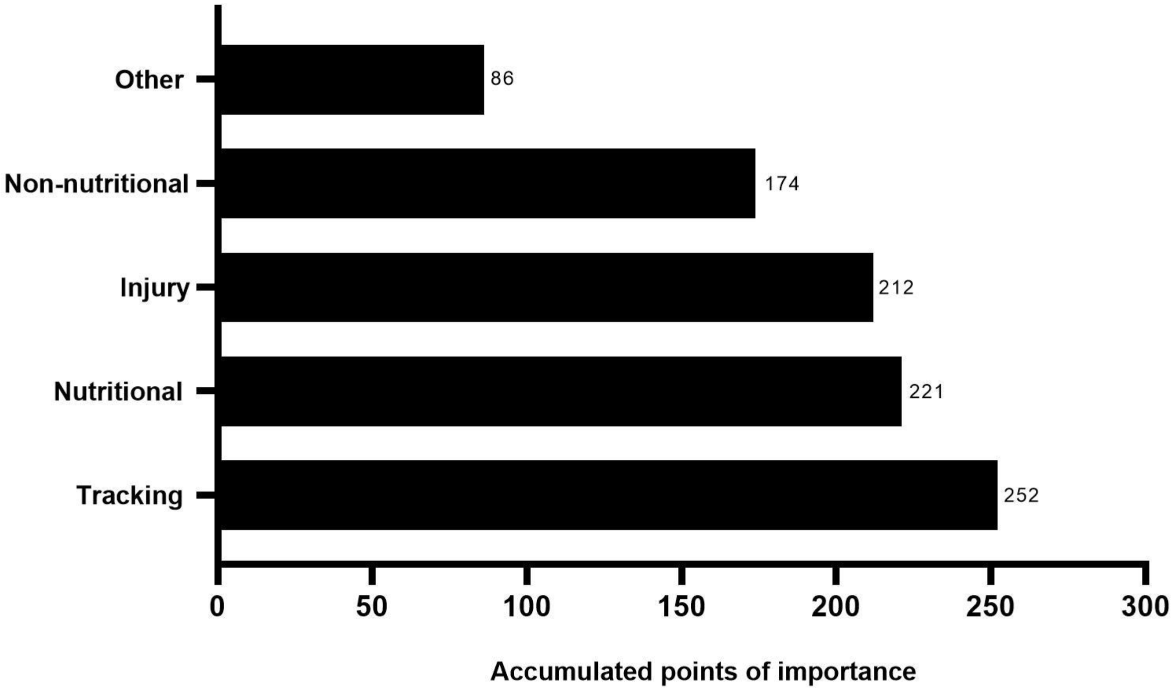

Figure 6.4. Practitioners perceived importance of areas for future research.

6.4 DISCUSSION

The present study develops knowledge in relation to applied practice and recovery strategies associated with the additional 30-min ET period. These survey data offer novel practitioner and coach insights, enhance understanding of applied practice, and highlight future research considerations for recovery following ET soccer matches. Collectively, these findings suggest that practitioners adapt recovery practices following ET matches, though support that further research in this area is warranted.

While half of the practitioners surveyed condition players outside of peak periods in preparation for matches that proceed to ET, the other half indicated that changes to conditioning practices were not implemented. Practitioners highlighted existing difficulties with maintaining training volumes across an entire season, especially during periods of fixture congestion (Julian et al., 2020a; Page et al., 2019). This challenge may impede maintenance of within-season training loads that are sufficient to prepare players for ET, whilst also ensuring adequate regeneration periods. It appears that some practitioners implement acute 'within-week preparation'; however, it is unlikely that using such strategies will elicit the desired adaptations in such a short timeframe (Harper et al., 2016c). Therefore, since fatigue-induced losses in strength are likely to occur during the latter stages of a match, players that are inadequately conditioned for the prolonged ET period may be susceptible to injury. Since practitioners in the current survey highlighted 'changes in acute injury-risk' as an important area for future investigation, epidemiological research is warranted to determine whether players are at an increased risk of injury during ET and subsequent matches.

Most practitioners 'agreed' to 'very strongly agreed' with the proposition that ET prolongs recovery and that practices should be adjusted accordingly. It was highlighted that practitioners extend the cool-down duration post ET matches, despite evidence that prolonged cool down durations have no effect on muscle soreness or glycogen resynthesis (Van Hooren & Peake, 2018). Those who do not change practice immediately post-match reportedly lack 'time' (e.g., 'you have to get on the bus as sometimes the driver may go over his hours with the delay to the end of the game'). This issue may be problematic following away matches from a logistical viewpoint, particularly for lower-league and semi-professional practitioners who have fewer resources available and are unable to intervene with acute strategies that are targeted at enhancing recovery immediately post matches that proceed to ET. This could be detrimental to player recovery considering ET has shown to evoke additional central fatigue, increase perceived muscle soreness and reduce blood glucose concentrations (Goodall et al., 2017; Stevenson et al., 2017; Winder et al., 2018). This highlights the importance of appropriate feeding strategies that can be implemented whilst travelling. 'Away match logistics' following ET matches was a topic of interest to a small number of practitioners and requires investigation.

A variety of practices were observed in relation to practitioners modifying nutritional intake immediately post and up to 24 hr following an ET match. The majority largely modulated carbohydrate and protein intake, rehydration practices, and used supplementation and polyphenols strategically in line with current evidence-based recommendations when limited time separates matches (Ranchordas et al., 2017). Though it has yet to be measured directly, ET matches could elicit a greater liver and muscle glycogen utilisation than 90 min and could have implications for adjusting carbohydrate guidelines following 120-min matches (Stevenson et al., 2017). While evidence suggests that consuming carbohydrate in the 5 min break prior to ET attenuates the reduction in dribbling performance (Harper et al., 2016d); there remains a dearth of clear evidence-informed guidelines for adapting consumption to aid recovery following this additional period of match-play. The survey respondents ranked this area of research as the second most important following 120-min match durations and thus should be explored.

Increasing the massage duration and intensity post-match was a notable adjustment made to post ET practice by approximately 15% of practitioners, despite its efficacy for recovery being largely ambiguous (for a review see Poppendieck et al. (2016)). Similarly, an increased duration with which cold water immersion and cryotherapy practices are employed were highlighted among ~20% of practitioners. Although, little evidence is available to support a dose-response relationship, recovery benefits after exercise are better established following cryotherapy (Rose et al., 2017). Nevertheless, practitioners individualised player recovery protocols, which is advised given that high inter-individual variations exist with recovery (Nédélec et al., 2012). This is an encouraging finding considering most of what is currently known about and adopted in relation to post ET match recovery modalities is derived from anecdotal observations or practices that have demonstrated efficacy following 90-min matches (Nédélec et al., 2013). Therefore, non-nutritional modalities and their recovery properties remain largely unexplored in response to ET and presents an avenue for future research.

Reductions in training loads and intensities were most pronounced at 24—48 hr after ET matches, broadly mirroring the additional rest periods also adopted at this period post 120 min of match-play. This may also be linked with teams typically having a rest day following a match regardless of duration (Malone et al., 2015). The importance of 'maintaining training intensities whilst reducing loads' (i.e., overall volume) was commonly highlighted among practitioners with 'training drills' (e.g., 'pitch sizes and drill times') manipulated to reduce physical output (e.g., 'high-speed running, accelerations, and decelerations'). Indeed, tapering training loads was highly dependent on the proximity of previous and upcoming matches, as opposed to whether the team had competed in an ET period. This could have detrimental implications for recovery potentially given that biomechanical loads are increased during simulated ET matches (Chapter 5). Given their unforeseeable nature, adapting training loads in response to ET matches requires versatility and carefully orchestrated periodisation to overcome the complexities associated with maintaining aerobic fitness whilst minimising the risk of load related injuries (Fitzpatrick et al., 2018). This remains a key challenge in the applied soccer environment, though with a contemporary practitioner endorsed rule change permitting the introduction of a fourth substitution during ET (Harper et al., 2016c; Hills et al., 2020), players exposed to excessive weekly loads may be identified and replaced. For those that are unable to be substituted, research that involves 'tracking the physical and physiological response' would help determine the extent to which recovery is impacted post ET. The survey data highlights that practitioners support research of this nature.

Though the current study received a high number of survey responses compared with other published works (Harper et al., 2016c; McCall et al., 2014), response rate alone may not reflect greater external validity (Morton et al., 2012). Consequently, it is advised that the findings of the current research are considered within the context of the limitations present, as the degree to which they elucidate the practices and perspectives of the teams that did not participate are uncertain. A convenience sample was used whereby personal networks were contacted, potentially introducing selection bias (Bethlehem, 2010), although this approach was used to ensure the dataset was limited to one response per team (Harper et al., 2016c). Practitioners were made aware of the survey topic prior to completion and thus, it is possible that selection bias was introduced in the study since the pool of participants may have had biased propensities towards this area of research. It is acknowledged that previous soccer surveys carried out inferential statistics to assess variances between stakeholders (Nosek et al., 2021; Weston, 2018), though it was not deemed appropriate in the current research, since participating practitioners from different levels and disciplines were not equally represented.

6.5 CONCLUSIONS

This study presents novel practitioner and coach insights and examines how recovery practices are managed following ET matches. Although ET conditioning approaches vary considerably between practitioners, many respondents return players to training based on fatigue markers following this period of match-play. Recovery practices are adapted in response to 120-min matches as practitioners believe that the additional 30-min period has negative implications for recovery. Training loads and intensities are tapered up until 48 hr post ET matches, though are mostly returned to normal by 72 hr. Future research considerations were overwhelmingly in support of tracking players' physiological and physical responses following ET. Therefore, it is recommended that the underpinning physiological and physical fatigue responses following soccer-specific activity are investigated to provide an increased understanding of the recovery process following matches of this duration.

7.0 THE IMPACT OF 120 MINUTES OF TREADMILL-BASED SOCCER-SPECIFIC EXERCISE ON RECOVERY

Publication arising from this chapter:

Field, A., Corr, L. D., Sarmento, H., Naughton, R. J., Clifford, T., Haines, M., Page, R. M., & Harper, L. D. (2020). The impact of 120 minutes of treadmill-based soccer-specific exercise on recovery. Research Quarterly for Exercise and Sport, Doi: 10.1080/02701367.2021.1964697.

Author contributions

Adam Field wrote the first draft of the manuscript, and collected and analysed all data. All authors reviewed the manuscript at various stages throughout the editing process. All authors read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

7.0.1 ABSTRACT

The ET period of soccer is frequently competed during fixture congested schedules with limited recovery time between matches. The aim of this study was to assess muscle damage recovery following 90- and 120-min (i.e., incorporation of ET) of simulated soccer match-play. Twelve semi-professional soccer players completed 90 and 120-min treadmill-based soccer-specific exercise in a counterbalanced order. The following measures were taken at baseline and immediately-, 24, 48 and 72-hr post-exercise to assess recovery: CK, creatinine, urea, AST, perceived muscle soreness (VAS), PPT, RSI, CMJ, and isokinetic peak torque assessments of eccKF and conKE at 60, 180 and 270 $deg \cdot s^{-1}$. No significant between-trial interactions except for CK were found. Pairwise comparisons detected a 53% increase in CK at 24-hr (455 ± 29 $\mu \cdot L^{-1}$) and a 58% increase at 72-hr following 120-min of simulated match-play (244 ± 25 $\mu \cdot L^{-1}$) versus the corresponding post 90-min time-points (24 hr: 299 ± 29 $\mu \cdot L^{-1}$, $p < .01$, 72 hr: 154 ± 29 $\mu \cdot L^{-1}$, $p = .02$). No interaction effects were detected for any other recovery variables. It was also identified that CK and perceived muscle soreness remained elevated up to 72-hr following both trials ($p < .01$). These data indicate that 120 min of simulated soccer match-play delays the time-course of CK recovery up to 72-hr post-match. However, 120 min of simulated soccer has no additional impact on functional recovery and perceived muscle soreness versus 90 min. Recovery should be investigated following 90- and 120-min of actual match-play.

7.1 INTRODUCTION

The physical demands of soccer matches involve a myriad of eccentric muscular efforts including sprints, jumps, rapid accelerations, decelerations and CoD elements (De Hoyo et al., 2016). Such activity can induce fatigue (a debilitating symptom) and perceptual stress, deplete endogenous substrates, and impose structural damage within muscle fibres (Harper et al., 2016d; Mohr et al., 2005; Stevenson et al., 2017). Mechanisms explaining these detrimental effects at the local level include an increased inflammatory response, disturbance to calcium homeostasis and ultra-structural damage to muscle fibres and connective tissues (Mohr et al., 2005; Nédélec et al., 2013; Proske & Morgan, 2001). Following these disturbances, recovery, defined as restoring homeostasis (i.e., returning players to pre-performance values), is paramount post-match (Nédélec et al., 2012).

When considering the evolving nature of contemporary soccer and the number of contextual factors that can influence the demands of the modern game, much attention has been given to understanding the issues associated with the fatigue and recovery response to soccer match-play. However, little research attention has been afforded to the impact of the additional period of ET on recovery. Traditionally, soccer is contested over 90 min, and as such, there is a wealth of literature documenting fatigue and subsequent recovery post matches of this duration (for a review see; (Nédélec et al., 2012). However, when matches are tied, and an outright winner is required during specific competitions, ET is required (Harper et al., 2016c). Matches that progress to ET are typically competed among the fixture congested scheduling associated with tournaments with insufficient recovery time between matches (Julian et al., 2020a). This may have additional implications if ET further impedes recovery. Furthermore, practitioners in Chapter 6 ranked tracking players' physiological and physical responses as the most crucial area of future research, and thus, investigating these responses following 120-min of soccer-specific activity is advocated. It must also be highlighted that the systematic review conducted in Chapter 2, identified that there is a lack of rigorous research investigating recovery following 120-min of soccer-specific exercise.

Previous empirical work examining five English Premier League reserve team players found explosive power (i.e., CMJ) was reduced and CK concentrations were increased at 24 and 48 hr post 120 min of match-play (Russell et al., 2015b). However, as players only competed in a single match that required ET and there were no comparisons to 90 min, it is difficult to discern the extent to which the additional 30-min duration further influenced the recovery response. Winder et al. (2018) monitored players competing in a micro cycle, with the second of three matches progressing to ET (i.e., 90, 120, 90 min). In the four professional players examined, the ET match negatively affected subjective measures of fatigue, muscle soreness, mood, as well as CMJ height when expressed relative to the initial 90-min match. Though these findings are indicative of impeded recovery following ET matches, and notwithstanding the high ecological validity of these studies, limitations such as small sample sizes (*n* = 5 and 4 players), insufficient control of confounders including dietary intake (Drust et al., 2013) and high inter-match variability associated with match-play reduce experimental rigour (Gregson et al., 2010).

The purpose of this study was to assess the recovery response following 90 and 120 min of treadmill-based simulated soccer under controlled conditions. It was hypothesised that recovery of the primary outcome measure, CMJ height, along with the other variables, would be impaired following 120 min versus 90 min of simulated soccer.

7.2 METHODS

7.2.1 Study design

Ten visits to the laboratory over a three-week period were required. The study comprised the completion of a 90 and 120-min trial. The study used a single-blinded, within-subjects, crossover design with trials completed in a counterbalanced order. The order was determined by a number generator that randomly allocated participants to a sequence of trials. The two trials were performed 9 ± 2 days apart to ensure recovery. To eliminate the influence of self-pacing on running technique (Waldron & Highton, 2014), participants were instructed that both trials could consist of 120 min; however, the protocol was either terminated at 90 min or ET commenced. Recovery measures were recorded at baseline, immediately-, 24, 48 and 72 hr post-trial. Dependent variables were measured in the following order: capillary blood sampling, perceived muscle soreness (VAS), PPT, RSI, CMJ and isokinetic peak torque tests.

7.2.2 Participants

Following institutional ethical approval, 12 male semi-professional soccer players (mass: 74 ± 8 kg; stature: 179 ± 3 cm; age: 22 ± 3 years; estimated $\dot{V}O_{2max}$: 59 ± 7 ml·kg·min^{-1}) with 13 ± 3 years soccer experience provided informed consent prior to data collection. An *a priori difference between two dependent means (matched pairs)* power calculation was undertaken using G*Power© (version 3.1.9.2, 2017, Germany) which deemed a sample size of 12 sufficient based on 80% $1 - \beta$, an α of .05, and a large ES (Cohen's d = 0.8) to detect differences in the primary outcome variable, CMJ. Participants were included on the basis that they attained $\dot{V}O_{2max}$ ≥ 48.5 ml·min·kg^{-1} as per previous ET work (Stevenson et al., 2017) and had no medical contraindications to exercise (e.g., musculoskeletal injury or asthma). Participants were asked to refrain from strenuous activity and prohibited from alcohol consumption, non-steroidal anti-inflammatory drugs (e.g., ibuprofen) and foods rich in polyphenols 72-hr prior and throughout testing. Dietary intake was recorded throughout the five testing days (24-hr pre-trial to 72-hr post-trial) via weighed food diaries and later analysed to assess macronutrient composition and caloric intake. Dietary intake was replicated as closely as possible for the subsequent trial. To assess compliance and food wastage, pictures were sent to the lead researcher on two days (pre-selected) during data collection (i.e., -24 and +48 hr of trial) using a free smartphone messaging application (WhatsApp). This ‘snap and send’ method has been used in previous research (Costello et al., 2017; Zhang et al., 2015a).

7.2.3 Preliminary visits and main trials

Mass (SECA 875 electronic flat scale, SECA, Germany) and stature (SECA 213 portable stadiometer, SECA, Germany) were taken during the preliminary visit and $\dot{V}O_{2max}$ was estimated via an incremental treadmill protocol. First, participants completed a standardised warm-up, whereby intermittent speed changes and a dynamic stretching sequence were incorporated. The incremental test followed, starting at a running speed of 10 $km \cdot h^{-1}$ and continued to increase by 1 $km \cdot h^{-1}$ every 30-s until 17 $km \cdot h^{-1}$, whereby the protocol inclined by 0.5° every 30-s until volitional exhaustion (refer to section 3.8.1 for further details). Second, another session was used to fully habituate participants with trial day procedures and the completion of a 120-min familiarisation trial. Upon arrival for the main trials, participants provided a mid-flow urine sample for measurement of urine osmolality (Osmocheck, Vitech Scientific, West Sussex, UK). Once baseline measures were taken, participants completed either 90 or 120-min protocol. Water and/or a carbohydrate electrolyte beverage was consumed *ad libitum*, recorded by the research team, and replicated for the subsequent trial. Lastly, post-trial recovery measures were collected, and participants vacated the lab.

7.2.4 Soccer simulation

A reliable (Chapter 4) and validated soccer-specific protocol (Page et al., 2015) was completed on a motorised treadmill (h/p/ cosmos pulsar® 3p: h/p/cosmos sports & medical GmBH, Germany). The protocol was structured as two x 45-min halves (separated by a 15-min HT break) and either terminated or continued following a 5-min rest period, with two additional 15-min periods (interspersed by a 2-min break). All breaks were passive, and the same activity profile was repeated every 15-min. Maximum sprint velocities reached 25 $km \cdot h^{-1}$ with changes in velocity set at the treadmill threshold (1.39 $m \cdot s^{-2}$). Similar to ET match-play, the participants performed 56 sprints and covered a distance of 16.26 km during the 120-min trial (Russell et al., 2015b; Winder et al., 2018). Participants were asked to provide d-RPE for discretely for

RPE-L, RPE-B and RPE-O in a randomised sequence to counteract order effects. These data were collected after each 15-min period of exercise through use of the 6—20 Borg scale (Borg, 1998). Similarly, the treadmill paused briefly at the cessation of each 15-min bout and a blood capillary sample was taken and later analysed for BLa (Biosen C-Line; EKF-diagnostic GmBH, Cardiff, Wales; CV both 1.5%). PlayerLoad™ (Catapult Innovations, Australia) data were continuously recorded throughout exercise to assess between trial responses.

7.2.5 Recovery measures

7.2.5.1 Blood sampling procedures and biochemical analyses

Finger-prick capillary blood samples were taken and analysed for CK, creatinine, urea and AST concentrations using procedures highlighted in section 3.9.1.1.

7.2.5.2 Muscle soreness

A subjective assessment of perceived muscle soreness was conducted using a VAS as per previously described methods (Howatson & Milak, 2009; Page et al., 2019). After adopting a squat position at a knee angle of approximately 90°, participants were asked to rate their lower-limb muscle soreness by marking on a 100 mm horizontal line (see Appendix 7). The scale ranged from 'no soreness' (0) to 'unbearably sore' (100) and the line placement was measured with a ruler and expressed in mm. Measuring muscle soreness using the above approach has been previously reported as a reliable method (ICC = 0.65, CV of 18.5%) (Rampinini et al., 2011).

A PPT assessment was undertaken on the dominant leg using a handheld Baseline Algometer (27.22 kg/ 60 lbs, Fabrication, Enterprises Inc., USA). The preselected pressure sites included the rectus (PPT_{RF}) and biceps femoris (PPT_{BF}). Contemporary epidemiological research has identified the thigh as the most common injury location in professional soccer (López-Valenciano et al., 2020), with the biceps femoris being the most injured (Schuermans et al., 2014). Additionally, the rectus femoris is susceptible to pain (Baker et al., 1997) and tightness (Björklund et al., 2001), but PPT investigations of these muscles have not been undertaken in response to a soccer exercise stimulus. Whilst participants adopted supine (for PPT_{RF}) and prone (for PPT_{BF}) positions, increasing pressure was applied at a constant rate using the circular flat tip (a surface of exactly 1 cm^2) of the algometer perpendicular to a marked cross positioned in the centre of the muscle belly. The centre of the muscle belly was probed because delayed onset muscle soreness occurs in the initial phase distal to the muscle belly (musculotendinous attachment), with pain spreading to the centre of the muscle belly by 48 hr in the quadriceps (Nie et al., 2005). The skin surface was marked by the lead researcher and re-applied daily using a permanent marker pen to enable between test consistency (Page et al., 2019). Prior to the initial test, it was explained to participants that the purpose of the assessment was not to measure pain tolerance/threshold, and that they were instructed to indicate when the sensation of pressure switched to pain. Recordings were taken twice for each site with ~60 s interspersing measurements to reduce temporal summation (Eckert et al., 2017) and the mean of both readings were presented for analyses in pounds (lbs). Moderate to excellent inter- and intra-rater reliability has previously been reported for such methods of PPT as evidenced by ICC's ranging from 0.63 to 0.97 (Binderup et al., 2010; van Wilgen et al., 2011; Walton et al., 2011).

7.2.5.3 Muscle function

For RSI, participants were instructed to drop from a 0.3 m platform and upon landing, jump maximally, whilst minimising ground contact time and maximising vertical jump height. The RSI values were calculated automatically using manufacturer software (Opto Jump, Microgate, Italy) through the sum of jump height (cm) divided by contact time (ms). Following a 30-s rest period, participants performed a CMJ with hands on hips, feet shoulder width apart and when prompted, descended into a squat (~60°), and jumped vertically with maximal effort. Jump efforts were measured using a portable optical measurement system (Opto Jump, Microgate, Italy) and were separated by a 30-s passive recovery period with the mean of three jumps being used for analyses (Harper et al., 2016d). Further details can be found in sections 3.9.2.1 and 3.9.2.2.

7.2.5.4 Isokinetic testing

Unilateral peak torque of the eccKF were measured using a Cybex HUMAC Norm isokinetic dynamometer with HUMAC2009 software version 0.8.4 (CSMI, USA). Each of three sets were performed at respective angular velocities of 180, 270 and 60 $deg \cdot s^{-1}$, with this order chosen to attenuate the possible fatiguing effect of slower speeds (Greig, 2008). Five reps of each of the three speeds were performed (i.e., three sets), which were interspersed by a 30-s passive rest period. The preferred kicking leg was assessed through a range of 0−90° (0° representing full extension and 90° full flexion). Once checked and calibrated, the dynamometer was setup specific to the participant for each session as per manufacturers guidelines. Whilst seated, participants were secured across the shoulders, pelvis and thighs to reduce excessive movement artefact. The femoral epicondyle of the knee was aligned with the crank axis of rotation and the cuff on the padded lever arm was placed 5-cm proximal to the malleoli. The contralateral limb was restricted by a padded support. Thereafter, the passive limb was weighed at anatomical zero (defined as full knee extension) and the effects of gravity were applied to torque data. During each rep, the limb weight contribution is calculated as the torque from the limb multiplied by the sine(angle). No verbal or visual feedback was provided throughout testing. For eccentric knee flexion at 180, 300 and 60 $deg \cdot s^{-1}$, similar soccer research has reported ICC's of 0.78, 0.76 and 0.78, respectively (Greig, 2008). For further details, refer to section 3.9.2.3.

7.2.6 Dietary analysis

Participant food diaries were input into dietary analysis software (Nutrimen.co.uk, Dark Green Media Ltd, ©2016). The estimated measurement error of inputting participant's dietary intake was calculated using the standard error of measurement (SEM) with 95% CIs. The SEM was derived from the square root of the mean square error from an ANOVA and expressed in the units of each given variable (Stratford & Goldsmith, 1997). In order to examine intra-rater reliability, three participants were selected at random, and a single researcher inserted the same three food diaries into the analysis software on six separate occasions during a six-week period. To assess inter-rater reliability, the same diaries were entered by three separate researchers twice in two-weeks.

7.2.7 Statistical analyses

Exploratory data analyses were undertaken to evaluate the assumptions associated with the LMM. This statistical method was chosen as an appropriate test for repeated measures designs that involve random and fixed level factors with data missing at random (Di Salvo et al., 2009). A visual inspection of q-q plots, histograms and boxplots was undertaken to assess normality of residuals. Thereafter, residuals > 3.0 SD from the mean values were removed prior to analyses in line with the assumptions of the LMM. A basic variance components assessment revealed the model AIC was best fit for each recovery variable. Initially, models were regarded as null and subsequently developed to more stringent models. A basic variance components model was utilised to calculate the intraclass correlation of the random factors (i.e., *participant*) to establish if a significant variance contributed to the recovery variables. Wald Z statistics were employed to assess the null hypothesis (i.e., that zero variance existed between participants); if rejected, the random factor of participant ID was included in the successive hierarchical models. The covariance structure of the random factors was set to variance components in all models. The AR-1 was established as the model most suitable for each recovery variable for the repeated measures of time. The fixed effects and their interactions included were *trial and time* for each model. All models estimated parameters using the maximum likelihood method. Least significant corrections were applied post-hoc with 95% CI of the difference reported. A paired samples T-test assessed differences between participant dietary intake across the five experimental days. Alpha was accepted at $p < .05$ prior to analyses. Data are expressed as mean and ± SE unless otherwise stated and were processed using IBM SPSS Statistics 26 for windows (SPSS Inc., Chicago, IL, USA).

7.3 RESULTS

7.3.1 Between trial measures

As outlined in Table 7.1, no differences were detected between trials for energy or macronutrient intake ($p > .35$). Urine osmolality was similar pre and post between the 90- and 120-min trials ($p > .79$). Environmental conditions remained similar between trials ($p > .33$). No differences were identified for cumulative PlayerLoad™ accrued between trials 90-min values ($p > .82$). Likewise, no differences were found for between-trial mean BLa, RPE-L, RPE-B and RPE-O responses ($p > .65$; Table 7.2).

Table 7.1. Mean energy and macro nutrient composition of participants diet across five days of testing for each trial and reliability of data input (mean ± SD)

	Mean dietary intake across 5 days			Inter-rater reliability		Intra-rater reliability	
Variable	**90 min**	**120 min**	***p* value**	**SEM**	**95% CI**	**SEM**	**95% CI**
Energy (Kcal)	2008 ± 577	1985 ± 486	.68	95	186	53	104
Carbohydrate (g)	237 ± 93	220 ± 67	.35	12	23	4	7
Protein (g)	109 ± 40	109 ± 47	.93	2	4	1	2
Fat (g)	75 ± 18	77 ± 18	.76	3	6	4	8

Table 7.2. Environmental conditions and responses across both trials (mean ± SD)

Variable	90 min		120 min	*p* value
Urine osmolality (pre; $mOsm \cdot kg^{-1}$)	536 ± 120	-	556 ± 167	.79
Urine osmolality (post; $mOsm \cdot kg^{-1}$)	516 ± 104	-	530 ± 160	.83
Humidity (%)	33.8 ± 3.5	-	33.3 ± 3.1	.66
Barometric pressure (%)	29.2 ± 0.4	-	29.4 ± 0.6	.79
Ambient temperature (ºC)	20.1 ± 0.9	-	19. 7 ± 1.1	.33
Variable	**90 min**	**90 min ($_{120\ min}$)**	***p* value**	**120 min**
PlayerLoad™ (a.u)	1359 ± 21	1347 ± 25	.82	1817 ± 25
Blood lactate ($mmol \cdot l^{-1}$)	2.4 ± 1.5	2.4 ± 1.5	.98	2.5 ± 1.5
RPE-L	12 ± 2	11 ± 2	.65	12 ± 2
RPE-B	11 ± 2	11 ± 2	.95	12 ± 2
RPE-O	12 ± 2	12 ± 2	.83	12 ± 2

Urine and environmental significance values are reported as differences between both 90- and 120-min trials.
90 min ($_{120\ min}$) = 90 min duration for the 120 min trial.
Responses to exercise significance values are reported as differences between the 90 min duration of both trials.
PlayerLoad™ values are reported as the cumulative response across the specified duration.
Blood lactate and RPE values are reported as the mean response per epoch of exercise.
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7.3.2 Variance calculations

Table 7.3 provides the ICC's (%) of the random factors accounted for in each of the LMMs. All recovery measures, except for CK, creatinine and AST, contributed significant variance to the dependent variables and were included as a random factor in the larger hierarchical models.

Table 7.3. The ICC's (%) of the random factor of participant ID for all recovery variables. Where significance was found, participant ID was included in the linear mixed model

Variable	**ICC (%)**
CK	14.73
Creatinine	20.57
Urea	41.49*
AST	11.47
VAS	46.32*
PPT_{RF}	85.03*
PPT_{BF}	63.65*
RSI	86.09*
CMJ	95.14*
$conKE_{180}$	72.73*
$conKE_{270}$	81.63*
$conKE_{60}$	75.19*
$eccKF_{180}$	57.77*
$eccKF_{270}$	64.27*
$eccKF_{60}$	66.24*

** Represents significant determinant of variance within the linear mixed model ($p < .05$).*

7.3.3 Recovery responses following 90 and 120 minutes of soccer-specific exercise

Interaction effects for trial and time were evident for CK (p = .01), with post-hoc comparisons revealing higher values at 24-hr post 120-min (455.1 ± 29.4 $\mu \cdot l^{-1}$; 95% CI = 396.7 to 513.7 $\mu \cdot l^{-1}$) compared to 24-hr following 90-min (298.8 ± 29.3 $\mu \cdot l^{-1}$; 95% CI = 240.6 to 356.9 $\mu \cdot l^{-1}$; 95% CI for diff = 75.1 to 237.8 $\mu \cdot l^{-1}$; p < .01). Furthermore, trial interaction effects were observed at 72-hr post 120-min (244.1 ± 24.7 $\mu \cdot l^{-1}$; 95% CI = 194.7 to 293.4 $\mu \cdot l^{-1}$) versus 72-hr following the 90-min simulation (154.1 ± 29.3 $\mu \cdot l^{-1}$; 95% CI = 240.6 to 356.9 $\mu \cdot l^{-1}$; 95% CI for diff = 17.2 to 176.9 $\mu \cdot l^{-1}$; p = .02). No interactions were identified for creatinine (p = .24), urea (p = .59), AST (p = .83), VAS (p = .22), PPT_{RF} (p = .99), PPT_{BF} (p = .78), RSI (p = .35), CMJ (p = .21), $conKE_{180}$ (p = .12), $conKE_{270}$ (p = .11), $conKE_{60}$ (p = .06), $eccKF_{180}$ (p = .75), $eccKF_{270}$ (p = .67) and $eccKF_{60}$ (p = .42).

Main effects for time were observed for CK, urea, VAS, PPT_{BF}, RSI, CMJ, $conKE_{180}$, $conKE_{270}$, $conKE_{60}$, $eccKF_{180}$, $eccKF_{270}$ and $eccKF_{60}$ (all p < 001); refer to Table 7.4 for time effects. No main effects for time were evident for creatinine (p = .24), AST (p = .23) and PPT_{RF} (p = .46).

Table 7.4. Recovery responses following 90 and 120 min of soccer-specific exercise (*mean ± SE)*

	Time				
Variable	**Baseline**	**Post**	**24 hr**	**48 hr**	**72 hr**
CK ($\mu \cdot L^{-1}$)					
90 min	102.7 ± 24.7	229.6 ± 25.6^{a}	298.8 ± 29.3^{ab}	258.6 ± 28.9^{ac}	154.1 ± 29.3^{acd}
120 min	109.4 ± 25.7	233.8 ± 26.8^{a}	455.1 ± 29.4*^{ab}	301.6 ± 30.8^{ac}	244.1 ± 24.7*^{acd}
Creatinine ($\mu mol \cdot L^{-1}$)					
90 min	77.6 ± 4.7	80.8 ± 4.9	79.9 ± 4.7	72.3 ± 4.7	74.2 ± 5.1
120 min	68.1 ± 4.9	89.6 ± 5.1	80.2 ± 5.1	77.1 ± 4.7	72.1 ± 4.9
Urea ($mmol \cdot L^{-1}$)					
90 min	6.64 ± 0.53	7.97 ± 0.53^{a}	8.05 ± 0.53^{a}	6.84 ± 0.52^{bc}	6.52 ± 0.55^{bc}
120 min	6.91 ± 0.52	9.01 ± 0.52^{a}	8.27 ± 0.54^{a}	7.48 ± 0.52^{bc}	7.51 ± 0.53^{bc}
AST ($\mu \cdot L^{-1}$)					
90 min	41.4 ± 3.2	44.01 ± 3.3	45.5 ± 3.2	39.6 ± 3.8	41.0 ± 3.4
120 min	38.0 ± 3.1	40.07 ± 3.2	44.5 ± 3.3	41.7 ± 3.4	37.9 ± 3.1
VAS					
90 min	2 ± 2	20 ± 2^{a}	22 ± 2^{a}	14 ± 3^{ac}	6 ± 3^{abcd}
120 min	1 ± 2	26 ± 3^{a}	23 ± 3^{a}	18 ± 2^{ac}	5 ± 2^{abcd}
PPT_{BF} (lbs)					
90 min	25 ± 1	25± 1	24 ± 1	24 ± 1	26 ± 1^{cd}
120 min	22 ± 1	22 ± 1	22 ± 1	22 ± 1	24 ± 1^{cd}
PPT_{RF} (lbs)					
90 min	22.59 ± 1.76	23.25 ± 1.76	22.92 ± 1.76	22.25 ± 1.76	23.21 ± 1.78
120 min	24.08 ± 1.76	24.00 ± 1.76	23.69 ± 1.78	23.50 ± 1.76	24.42 ± 1.76
RSI (a.u)					
90 min	1.41 ± 0.12	1.31 ± 0.12^{a}	1.30 ± 0.11^{a}	1.31 ± 0.11^{a}	1.37 ± 0.12^{bcd}
120 min	1.33 ± 0.12	1.26 ± 0.12^{a}	1.23 ± 0.12^{a}	1.25 ± 0.12^{a}	1.40 ± 0.12^{bcd}
CMJ (cm)					
90 min	36.6 ± 2.2	35.4 ± 2.2	34.9 ± 2.2^{ab}	35.3 ± 2.2^{ac}	36.6 ± 2.2^{ce}
120 min	36.4 ± 2.2	36.3 ± 2.2	34.9 ± 2.2^{ab}	36.0 ± 2.2 ^{ac}	36.5 ± 2.2^{ce}
$conKE_{180}$ (Nm)					
90 min	157.8 ± 6.3	151.9 ± 6.3	149.5 ± 6.3	149.5 ± 6.3	157.5 ± 6.4^{abc}
120 min	147.2 ± 6.3	150.9 ± 6.4	152.9 ± 6.5	154.5 ± 6.4	158.6 ± 6.4^{abc}
$conKE_{270}$ (Nm)					
90 min	120.3 ± 4.8	119.2 ± 4.8	115.8 ± 4.8	122.2 ± 4.8	122.6 ± 4.8^{abc}
120 min	115.0 ± 4.8	114.8 ± 4.8	116.9 ± 4.8	115.2 ± 4.8	123.8 ± 4.8^{abc}
$conKE_{60}$ (Nm)					
90 min	198.8 ± 9.8	198.7 ± 9.9	197.0 ± 9.8	192.9 ± 9.8	208.0 ± 9.8^{ab}
120 min	188.4 ± 9.9	187.0 ± 9.8	198.5 ± 10.0	200.3 ± 9.8	196.7 ± 9.9^{ab}
$eccKF_{180}$ (Nm)					
90 min	160.4 ± 8.7	153.4 ± 8.7^{a}	146.0 ± 8.7^{a}	154.3 ± 8.8	163.8 ± 8.9^{bcd}
120 min	162.3 ± 8.7	145.2 ± 8.7^{a}	145.9 ± 8.9^{a}	153.8 ± 8.7	163.7 ± 8.8^{bcd}
$eccKF_{270}$ (Nm)					
90 min	159.4 ± 8.8	153.7 ± 8.8^{a}	152.8 ± 8.8^{a}	160.4 ± 8.9^{bc}	164.5 ± 8.9^{bc}
120 min	159.0 ± 8.8	147.1 ± 8.8^{a}	145.5 ± 8.9^{a}	161.8 ± 8.8^{bc}	167.5 ± 8.8^{bc}
$eccKF_{60}$ (Nm)					
90 min	164.1 ± 7.6	148.9 ± 7.6^{a}	142.5 ± 7.5^{ab}	148.0 ± 7.5^{ac}	159.0 ± 7.5^{c}
120 min	159.5 ± 7.6	147.2 ± 7.5^{a}	137.9 ± 7.7^{ab}	149.3 ± 7.5^{ac}	160.7 ± 7.5^{c}

Note. CK = creatine kinase = AST = aminotransferase, PPT = pain pressure threshold, $_{RF}$ = rectus femoris, $_{BF}$ = biceps femoris, RSI = reactive strength index, CMJ = countermovement jump height, conKE = concentric knee extension, eccKF = eccentric knee flexion, $_{180}$, $_{270}$, $_{60}$ denotes isokinetic angular velocities ($deg \cdot s^{-1}$).
**Represents significantly higher value for specified time point between trials.*
$^{a-d}$ Represents significant difference for time from baseline, post, 24 and 48 hr respectively.

7.4 DISCUSSION

The purpose of this study was to assess recovery in response to a 90- and 120-min (i.e., inclusion of an ET period) simulated soccer match. No differences were established between trials for all variables aside from CK. Higher CK activity was observed at 24 and 72 hr post 120 min of simulated soccer compared with a typical 90 min duration. Contrary to the study hypothesis, there was little evidence that recovery is prolonged after 120 min versus 90 min of simulated soccer match-play.

Despite most variables demonstrating that recovery is not further impeded following ET, the current findings demonstrate that compared to the 90-min trial, CK activity increased by a further 53% and 58% at 24 and 72-hr following 120 min, respectively. The magnitude of change in CK far exceeds the intra- and inter-assay measurement error (i.e., CVs = 1.4—2.1% and 1.5—4.2%, respectively), indicating the variation is low enough not to obscure a true experimental effect. Considering the CK response to 120 min alone, a 317% increase at 24-hr post-trial was observed versus baseline. Previous ET match-play investigations observed a 236% increase in CK at 24-hr post 120 min of soccer match-play versus baseline in professional players (Russell et al., 2015b). The higher magnitude of change in the current study compared to previous research is potentially explained by a wealth of factors such as standard of player and innate blood marker variability (Baird et al., 2012), though it is speculated most likely as a consequence of the differences in exercise modality (i.e., simulation vs match-play). This supports that the current treadmill protocol was sufficiently intense to induce a muscle damage response comparable with match-play and suggests recovery strategies may need to be modulated to restore the physiological perturbations of players competing for 120 min. Notwithstanding, it is important to note that CK has been criticised as a marker of muscle damage recovery (Twist & Highton, 2013), and therefore this finding should not be interpreted independent of the functional measures discussed below.

No between-trial interactions were present for eccKF peak torque in the current study, although the soccer-specific exercise protocol reduced eccKF peak torque following both exercise durations. Due to the logistical complexities associated with collecting isokinetic peak torque data during match-play, comparable data are not available following 90 min or ET matches. However, a similar investigation also demonstrates that completing an ET match simulation on a treadmill, significantly reduces eccKF peak torque, at the same speeds to the present study, immediately post 120 min of soccer-specific exercise (Chapter 5). Therefore, the current research supports previous data and contributes new information that indicates the deficits in eccKF persist up to 24 hr and return to baseline at 72 hr following 120-min of soccer. It is importtant to note, however, that matches are occasionally interpersed by ~48 hr (Ranchordas et al., 2017), and thus, practitioners are advised to closely monitor recovery markers, before returning players to training and matches. This proposition may not be considered realiastic in the real-world and other factors (preferred team selection, availability, formation, opposition etc) might be prioritsed. However, ideally, the recovery of maximal strength should largely be considered on an indvidual basis, depsite the current research reporting an average response, since eccKF strength characteristics are susceptible to large individual variation following ET (Chapter 5). It is advised that replacements are used strategically during or before the additional 30 min ET period to attenuate the effects of fatigue, and maintain fitness and freshness since a fourth substitution is now permitted during ET (Hills et al., 2020). This is especially important considering that the residual fatigue-induced decrements in eccKF in the intervening post match period, may contribute to the increased injury incidence during ET (Aoki et al., 2012), especially if players are not entirely recovered prior to the next competitive encounter. Epidemiological research, therefore, appears warranted to determine the extent to which ET matches exacerbate injury incidence in subsequent training and matches.

No differences were observed for conKE between the 90 and 120-min trial duration. There are no comparable data assessing isokinetic peak torque of the knee extensors following simulated or actual ET matches. However, following 90 and 120-min of soccer-specific activity, a 20% and 27% reduction in maximal voluntary force of the knee extensors was established versus baseline, respectively (Goodall et al., 2017). The deficits in conKE from baseline to post exercise in the current research were to a much lesser degree and non-significant. However, time effects were apparent, but values were signficantly higher at 72 hr compared with baseline after both trial durations, indicative of systematic bias or a priming effect. The learning effect is explained by the advantage of gaining and benefiting from a previous experience or in performance testing could be linked to an enhanced effort or motivation to improve (Hopkins, 2000). This suggests that one familiarisation trial was not sufficient to preclude participants performing better in the second trial than the first. The limb is isolated during the motion of conKE peak torque measures and the movements involved are not multiplex, nor do they require motor skill acquisition that neccessate more practice to learn effectively (Wulf & Shea, 2002). Previous research investigating isokinetic trunk strength testing, which demonstrates a learning effect is present between the first and second testing session, but not between the second and third measurement (Cowley et al., 2009). Therefore, it appears that several familiarisation trials may have been adequate to minimise learning effects for assessing conKE peak torque across varying isokinetic speeds in athletic populations. As such, the current data are to be interpreted with the above in mind.

Soccer-specific activity involves repetitive eccentric to concentric actions, that can induce neuromuscular fatigue and reduce peak power output (Nédélec et al., 2012). As such, given the functional relevance of such markers and their ability to detect perturbations in muscle function and elastic energy usage (Oliver et al., 2008), RSI and CMJ were used as indicators of exercise-induced fatigue. Time-dependent reductions in RSI and CMJ were evident up to 48-hr following both trials in the current research, although no between-trial differences were identified for these measures. Several studies have shown that the recovery of these markers is prolonged following 90 and 120 min of simulated and actual match-play (Abbott et al., 2019; Russell et al., 2015a; Thomas et al., 2017; Winder et al., 2018). Therefore, although the muscle function data limit inference concerning how player recovery should be managed following ET, the results add to an expanding body of literature that suggests recovery may need to be considered alongside the congested fixture periods associated with major tournaments (Julian et al., 2020a; Page et al., 2019). However, given that ET may not further prolong recovery of muscle function, there appears to be little need to adapt practice and provide additional measures to restore muscle function capacity irrespective of match duration.

An increased presence of blood urea was evident immediately post-exercise in both trials, and although differences did not reach statistical significance, these values were further (~10%) increased immediately following the 120-min exercise trial. Given macronutrient intake was similar between trials (Table 7.1), this finding, although speculative, is indicative of an increased protein degradation following ET. Urea is strongly associated with training volume potentially owing to the upregulation of gluconeogenesis during exercise that results in the breakdown of structural proteins (Haralambie & Berg, 1976; Meyer & Meister, 2011). The rate of gluconeogenesis is increased when glycogen stores are depleted and is stimulated by the secretion of glucagon, which can be linked to an upregulation in lipolysis (de Sousa et al., 2019; Shephard, 1999). This finding may corroborate previous research that suggests glycogen depletion and an increased rate of lipolysis is apparent during ET (Harper et al., 2016a; Harper et al., 2016d; Stevenson et al., 2017). This could potentially highlight the importance of modulating fuelling strategies, including carbohydrate intake prior and during, as well as adapting protein intake post ET matches. However, this research provides a foundation for future lines of exploration that are warranted to assess substrate metabolism using invasive techniques (i.e., muscle biopsies, venepuncture etc.) following 120 min of soccer-specific exercise.

Limitations are present within the current study that should be acknowledged. Indeed, actual match-play involves contacts with other players and additional movements such as cutting manoeuvres that could place disparate levels of stress on the musculoskeletal system, which potentially evoke a distinct muscle damage response (Castellano et al., 2011). It is well accepted that disparate physical loads, such as those experienced during match-play, can impact upon the muscle damage recovery response (Nédélec et al., 2012). Therefore, a decision was taken to use a valid treadmill design that employs fixed running velocities of an equal exercise volume to ensure that differences in the recovery response occurred as a result of the additional 30-min duration rather than player pacing strategies to offset fatigue. Another limitation of the study was that the protocol elicited a physiological response (BLa: 2.4 ± 1.5 $mmol \cdot l^{-1}$) near the lower end of the ranges previously reported during match-play (2—10 $mmol \cdot l^{-1}$) (Bangsbo et al., 2007). This is a common observation with treadmill variants (Greig et al., 2006; Page et al., 2015), although, the mechanical strain emulates a match more closely, with the current protocol eliciting a comparable muscle damage response to elite soccer match-play (Malone et al., 2018).

7.5 CONCLUSIONS

In summary, this study highlights that simulated soccer match-play 120 min in duration is associated with increased CK compared with a typical 90-min duration. However, there were no other trial and time interactions, suggesting ET has no further effect on the muscle damage recovery response. Collectively, these data might have implications for practitioners responsible for managing training and match loads during fixture dense tournament scenarios where ET periods are common. There appears to be little need (according to the current data) for adapting recovery practices in response to an ET match during fixture congested micro cycles and training can proceed as normal. Moving forward, recovery and subsequent performance should be investigated following 90- and 120-min of actual match-play.

8.0 GENERAL DISCUSSION

This main purpose of this chapter is to synthesise and contextualise the conclusions derived from the findings within this thesis. The section will also elucidate the practical applications that can be drawn from the data obtained, whilst highlighting the methodological limitations present across the progression of investigations carried out in the current thesis. Future research directions will then be proposed to further research in the ET period of soccer, and the findings will be explicitly summarised.

8.1 SUMMARY OF FINDINGS AND ORIGINAL CONTRIBUTIONS TO KNOWLEDGE

This thesis provides original perspectives and offers novel insights into the ET period of soccer. The contribution to new knowledge is based upon the critical appraisal of the ET literature and is derived through the collection of original data in each of the studies. The primary contribution to knowledge is based on the novelty of experimental mechanistic data that uses a rigourous, laboratory-based approach to examine numerous aspects of ET. A summary of each study is provided below, which outlines some of the specific novel contributions of this thesis.

The systematic review in **Chapter 2** sought to appraise the key ET literature with the intention of highlighting gaps, and thus, aspects of this additional period of match-play that require future consideration. It was apparent that despite investigations into some aspects of ET, areas that were lacking in research rigour and magnitude were assessments into the biomechanical aetiology of fatigue, substrate utilisation, and recovery responses. This was particularly evident in relation to controlled experimental investigations under standardised conditions.

There existed an absence of reliable soccer-specific treadmill-based protocols over the course of 120-min. Therefore, a soccer-specific treadmill-based simulation was adapted in duration (i.e., an additional 30 min was incorporated) and the reliability of the biomechanical and physiological responses were assessed over 120 min in **Chapter 4**. The responses to the adapted 120-min soccer-specific protocol were deemed moderately-to-strongly reliable. The secondary aim was to assess the biomechanical and physiological responses across 120-min of simulated match-play. PlayerLoad™ values increased during ET, indicative of reduced running efficiency, and a reduction in RER was also observed during ET, which suggests a shift in primary substrate usage (i.e., from aerobic glycolysis to lipolysis).

Using the reliable 120 min soccer-specific protocol, **Chapter 5** identified that indices of biomechanical performance are negatively influenced by ET. Specifically, EMG of the rectus femoris significantly reduced during ET, suggesting that central fatigue may be present in response to prolonged soccer-specific activity. Significant peak torque impairments in the eccKF were also observed across all isokinetic speeds post 120 min of soccer-specific activity versus pre-match. Changes in PlayerLoad™ corresponded with EMG activity for the rectus femoris, but there were no correlations for all other lower-limb fatigue responses. Additionally, the changing patterns of this PlayerLoad™ were entirely consistent with Chapter 4, thus substantiating these findings.

The survey data retrieved in **Chapter 6** from soccer practitioners working in semi-professional and professional soccer demonstrated that most respondents believe ET negatively impacts recovery and that practices must be tailored following ET versus a traditional 90-min match. It was also apparent that ET conditioning practices differ across practitioners, and many of them promote the return of players to their original schedules subject to individual fatigue assessments following ET. The practitioners were overwhelmingly in favour of future research being carried out on recovery in response to ET and 'tracking players physiological and physical responses' was their most important area of future research.

Chapter 7 was informed by the practitioner survey data, with 'tracking players physiological and physical responses' being ranked as the most warranted area of recovery and ET research. Players performed both 90 and 120-min of the treadmill-based simulation and recovery was monitored for the following 72 hr period. Whole blood CK markers were elevated post 120-min of soccer-specific exercise compared with the 90-min trial. However, none of the other blood, functional or subjective markers of muscle damage recovery were exacerbated by the ET simulation.

8.2 BIOMECHANICAL RESPONSES TO 120 MINUTES OF SOCCER-SPECIFIC EXERCISE

Biomechanical analyses were adopted throughout this thesis to elucidate how fatigue can contribute to running technique alterations and, although speculative, injury aetiology during ET. The evaluation of kinematic and kinetic patterns during actual competitive matches is not feasible and breaches soccer governing body rules. Therefore, the adoption of a laboratory treadmill-based soccer-specific exercise was deemed appropriate for evaluating the biomechanical measures utilised throughout the thesis. The standardised bouts of running implemented within treadmill protocols eliminate the self-pacing element associated with match-play and other soccer-specific exercise protocol designs. This enables conclusions drawn from the data to be attributed to a fatigue-induced state of inhibited performance capacity. The reliability indicators in Chapter 4 indicated that the responses to the treadmill protocol yielded good retest agreement and low measurement error. This accuracy of measurement gives researchers and practitioners confidence in the changes for effective practical use (Atkinson & Nevill, 1998). That is to say that changes to performance variables are due to experimental interventions and not natural noise or random error (Hopkins, 2000), in contrast to studies using soccer match-play (Gregson et al., 2010).

With the above in mind, the findings from Chapter 5 indicate that EMG_{RF} activity were substantially reduced during the final 15 min of ET, relative to the initial 30 min and the first 15 min after HT, despite an observed plateau-like trend in EMG_{BF} across the entire 120 min trial. Furthermore, there were no changes in conKE from pre-to-post 120 min, which suggests a downregulation of activity to protect and reduce the number of sprints that were performed during match play. In view of the standardised nature of the protocol, evidence suggests that there is a compensation from other musculature to achieve the same output. For instance, this compensatory mechanism could explain the deficits in eccKF peak torque, as the hamstrings may have generated a higher degree of propulsion to offset the lack of quadriceps activation during the protocol. This reduced activation also plausibly influences sprinting mechanics considering the high levels of neural activation required to recruit fast twitch type II fibres (Ross et al., 2001). The rectus femoris comprises a higher number of fatigue-sensitive FTx fibres versus other quadricep muscles (Krustrup et al., 2004), with this fibre type distribution disproportionate to the more fatigue-resistant composition of the biceps femoris (Dahmane et al., 2006). Therefore, it appears that since the rectus femoris contains a high fast twitch fibre percentage, there is likely an increased threshold of EMG and neural potentiation required to induce muscle contractions (Ross et al., 2001). Accordingly, the fatigue-induced decrements in the ability to recruit fast twitch motor units in the rectus femoris could be a contributory mechanism that underpins decrements in sprint performance during the ET period (Harper et al., 2016a; Harper et al., 2016b; Harper et al., 2016d; Kubayi & Toriola, 2018; Peñas et al., 2015; Russell et al., 2015b; Stevenson et al., 2017).

Reductions in eccKF peak torque were identified at 60, 180 and 270 $deg \cdot s^{-1}$ in Chapter 5 following ET. This finding appears consistent with 90 min simulated soccer observations (Cohen et al., 2015; Marshall et al., 2014; Small et al., 2010) and supports the patterns of fatigue experienced late during each half of match-play (Weston et al., 2011b). However, between-participant heterogeneity in torque changes were observed with decreases in strength of up to 34% for some participants and improvements of up to 21% in others. Previous investigations containing a sub-group analysis of ‘responders’ and ‘non-responders’ established that eccentric hamstring torque changes following a Nordic hamstring intervention were largely heterogeneous between individuals (Seymore et al., 2017). For instance, neutral, or negative responses were observed in some participants (‘non-responders’), whilst marked torque increases were observed for other participants. Therefore, eccKF peak torque alterations — whether it be strength decrements following exercise or strength adaptations to training programmes — must be considered individually. The distinct profiles are reportedly linked with muscle architecture variances in fascicle length, muscle thickness, pennation angle, and muscle cross-sectional area (Cuthbert et al., 2020). Research also indicates that soccer players with low eccKF strength and short biceps femoris long-head fascicles are prediposed to hamstring strain versus those possesing high eccKF strength and longer fascicles (Timmins et al., 2016a). Therefore, although these data are exploratory, players that have specific muscle properties may be susceptible to fatigue-induced strength-deficits in response to prolonged soccer-specific exercise, with such functional alterations possibly exposing players to injury during ET. Therefore, this outlines that focusing on average data obscures the innate variability in strength alterations, which are important considerations for injury screening in soccer players.

Muscle strength and motor unit recruitment patterns have been monitored throughout simulated soccer-specific exercise (Page et al., 2019; Rahnama et al., 2006). External load metrics such as PlayerLoad™ are used as practically appropriate surrogates to monitor fatigue patterns. In Chapter 4 and 5, PlayerLoad™ trends were similar across the 120 min duration, with both trials demonstrating an increase during ET. It is important to consider that increases in PlayerLoad™ in response to standardised running output such as the current investigations indicate an impaired locomotion efficiency. Evidence suggests that athletes self-optimise stride frequencies and lengths to minimise metabolic cost (Hunter et al., 2017). However, fatigue during running can translate to external kinematic alterations which can influence stride characteristics and contribute to changes in running economy (Hunter & Smith, 2007). Therefore, the increases in PlayerLoad™ may be associated with fatigue-induced decreases in stride length, which have shown to influence lower-limb shock attenuation during the stance phase of running (Mercer et al., 2003) and compromise spring-like properties of the musculotendinous unit (Maloney & Fletcher, 2018). Therefore, an impaired vertical stiffness (evidenced by non-significant reductions in $PL_{v\%}$ during ET) and capacity to minimise soft-tissue vibrations from impact forces (Wakeling et al., 2001), particularly when in a compromised state of fatigue could explain the injury aetiology that are inferred from the changes in PlayerLoad™. Therefore, although speculative, the current results indicate that players may modulate running technique in a sub-conscious attempt to minimise acute injury susceptibility during ET (i.e., increased PlayerLoad™). However, players in matches can employ pacing approaches to offset fatigue, thus, this signal could be lost to noise during matches, hence the reduction in physical performance metrics identified during this additional 30 min period of match-play (Kubayi & Toriola, 2018; Peñas et al., 2015; Russell et al., 2015b). Therefore, the current protocol can be used as a monitoring tool for standardised activity over 120-min to assess changes in fatigue.

There are presently few epidemiological studies that include ET data. Research prospectively assessing injury incidence across 15 seasons in professional Japanese soccer found that contact injury was greater during last 15 min of full-time and ET (Aoki et al., 2012). However, these data are not reflective of contemporary injury patterns and do not include comprehensive assessments of non-contact related injuries. Therefore, the relationship between ET and injury-risk is not well understood. The current research provides preliminary data that supports injury occurrence during ET under conditions where the same intensity is maintained throughout the entirety of a match. However, since a consistent exercise intensity is not sustained in the field (Russell et al., 2015a), it is unclear the extent to which these findings can infer injury. Notwithstanding, should the same output be achieved through the match, the causal pathway to injury during ET might be related to changes in stiffness and neuromuscular control (Oliver et al., 2014). This could possibly lead to alterations in the absorption properties of soft tissues and an increased stress response (Hughes & Watkins, 2008), which could result in an increased injury-risk. Another risk factor for competing in ET, could be the spike in weekly training loads and residual fatigue. It is well established that rapid increases in training load can exacerbate injury-risk (Drew & Finch, 2016; Eckard et al., 2018), with ET causing such unanticipated spikes in training load within a weekly microcycle. Such unprescribed increases in training load could impede recovery, which could lead to a reduced motor control impacting technique during unanticipated movements (Silva et al., 2018). Therefore, given the findings of this thesis demonstrates an impairment in strength and additional fatigue during ET, further investigation is required. This research could evaluate mechanisms of injury through epidemiological research that takes a longitudinal stance on collecting data across numerous seasons and multiple tournaments. Such studies could assist practitioners with designing injury prevention programmes in order to prepare players for ET prior to major tournaments.

Chapter 5 monitored the PlayerLoad™ response in conjunction with lower-limb fatigue patterns of EMG and torque to determine whether MEMS devices placed at the scapulae were sensitive to detect lower-limb fatigue patterns. Devices placed at the upper trunk, although required for optimising GPS signal strength during matches, only partially corresponded with lower-limb fatigue patterns. In absolute terms, planar-loading patterns from the first to the last bout of exercise, indicated by PL_{Total} (E1: 100 ± 4 — E8: 87 ± 4 a.u), PL_{V} (E1: 115 ± 5 — E8: 124 ± 5 a.u increased) and $PL_{A\text{-}P}$ (E1: 52 ± 3 — E8: 58 ± 3 a.u) were largely in line with changes in EMG_{RF} (E1: 100 ± 4 — E8: 87 ± 4 %; all $p < .05$), but not EMG_{BF} (E1: 100 ± 3 — E8: 103 ± 4 %; $p > .05$). This suggests that the increasing tri-axial movement body accelerations are reflective of reductions in the motor unit recruitment for the rectus femoris and mirror fatigue-induced changes in fatigue and movement quality. The reduced neural drive to the rectus femoris may place additional demands on the hamstring musculature, which may explain the impaired eccKF peak torque following ET. However, decreasing stride length in an attempt to minimise hamstring strains has been observed previously in soccer players (Small et al., 2010), possibly via compensatory planar changes in PL_V and PL_{A-P}. Furthermore, considering the standardised running profile, decreases in stride length must be reciprocated with greater stride cadence (Page et al., 2015). This requires modifications in natural running technique, which could exacerbate injury-risk and performance during ET to compensate for the reduction in EMG_{RF} and eccKF. Therefore, although the changes appear partially associated, correlational analyses should be performed to provide measures that can be used as practical alternatives to assessing fatigue in the lower limbs.

The current section highlights some of the biomechanical mechanisms, akin to soccer, that potentially elucidate the transient performance reductions observed during ET. However, the precise aetiology of fatigue is not well understood, but must be considered holistically to facilitate a comprehensive depiction of the many factors that underpin this debilitating phenomenon.

8.3 PHYSIOLOGICAL RESPONSES TO 120 MINUTES OF SOCCER-SPECIFIC EXERCISE

It is well established that participation in soccer-specific exercise and match-play results in high levels of temporal fatigue and physical performance decrements (Bangsbo et al., 2006; Bendiksen et al., 2012; Krustrup et al., 2006; Mohr et al., 2003, 2005). However, the current understanding of the aetiology of fatigue across both 90 and 120 min durations is limited. It is hypothesised that the physiological and metabolic factors that contribute to fatigability in soccer, include, dehydration (Nédélec et al., 2012), limitations in energy supply (Bendiksen et al., 2012), disruptions to muscle ion homeostasis (Mohr et al., 2003), factors impeding force development capacity (Rampinini et al., 2011), and shifts in substrate contribution (Bangsbo et al., 2006). In Chapter 4, a progressive shift in substrate utilisation (glycolysis to lipolysis) was observed, which was exacerbated during the ET period. However, although endogenous fuel sources such as glucose are challenged in response to prolonged soccer-specific activity, the primary energy yield during ET was provided through the glycolytic pathway. This suggests that glucose levels are sufficient to contribute more predominantly to energy metabolism, despite the absence of a pre-match meal or within-trial feeding strategies. However, considering the absence of within-match nutritional provision resulted in a shift in reliance towards lipid metabolism during ET, this reiterates the need for carbohydrate intervention at the earliest opportunity during a match and post 90 min.

Previous research has shown that fatigue is attributed to muscle glycogen depletion during intermittent exercise (Foskett et al., 2008) and 90-min soccer matches (Krustrup et al., 2006). Previous research assessing blood markers over 120 min of soccer-specific exercise observed a trend for changes in substrate utilisation synonymous with the current data (Harper et al., 2016d; Stevenson et al., 2017). In the placebo condition (i.e., no carbohydrates), increases in glycerol, NEFA and adrenaline, concomitant with reductions in insulin, blood glucose and lactate were observed during ET. The changes (elevations in adrenaline glycerol and NEFA, alongside reductions in insulin, blood glucose and lactate) correspond with a study where participants also completed 120 min of soccer-specific exercise (Harper et al., 2016d). This investigation involved the participants consuming a breakfast meal following an overnight fast and consumption of water at HT and a combined water and two 66-g energy-free electrolyte gels prior to ET. Therefore, the current findings substantiate that competing in an ET period without exogenous carbohydrate further impacts substrate depletion (Harper et al., 2016d; Stevenson et al., 2017). Furthermore, muscle glycogen content does not appear to be replenished back to baseline levels until between 2- and 3-days post soccer match (Jacobs et al., 1982; Krustrup et al., 2011). Accordingly, such results may have important implications for recovery, since further muscle fibre glycogen depletion following ET may hinder performance in subsequent training sessions and matches.

In the present research, standardised blocks of soccer-specific activity were performed across the 120 min trial. Therefore, it was surprising to find that BLa accumulation peaked up to 90 min then reduced considerably during ET. These findings are similar to previous research, whereby BLa levels peaked at the end of 90 min, though reduced markedly during ET (Stevenson et al., 2017). It is possible that the break prior to ET was sufficient for BLa clearance, although could be explained by the metabolic pathway involved with the maintenance of blood glucose, termed gluconeogenesis. This process involves hepatic and renal conversion of non-carbohydrate sources, including lactate, glycerol, and amino acids into glucose (Meyer et al., 2003). Therefore, this could explain the notion that the low BLa concentrations observed are linked with the lesser endogenous carbohydrate present during ET. For instance, gluconeogensis, with specific reference to the production of glucose from lactate, was likely stimulated to fuel exercise during ET, explaining the reduced levels of circulating BLa. Futhermore, evidence indicates that adrenaline increases markedly during ET (Stevenson et al., 2017), with adrenaline stimulating gluconeogenesis and promoting hepatic glucose formation (Sherwin & Sacca, 1984). Lactate has also shown to be the main precursor in adrenaline-stimulated gluconeogenesis (Meyer et al., 2003), thus suggesting that the peak in BLa values at the end of 90 min may have stimulated the gluconeogenic pathway. Additionally, lower BLa is indicative of a shift towards lipolysis as it is not a by-product of such a pathway but is the end-product of glycolysis (Rogatzki et al., 2015). Therefore, these findings corroborate the supposition that the reduced BLa concentrations during ET are associated with increased rates of gluconeogenesis in response to glucose depletion rather than reductions in physical performance intensity observed during ET (Kubayi & Toriola, 2018; Peñas et al., 2015; Russell et al., 2015b).

Differential ratings of perceived exertion provide additional information that discriminate between distinct internal effort perceptions using physiological mediators and could provide a pragmatic and time-efficient approach to monitoring load (Barrett et al., 2018; Macpherson et al., 2019; McLaren et al., 2016; McLaren et al., 2020; Weston et al., 2015). For all distinct sensory inputs in Chapter 4, d-RPE progressively increased across the entire 120 min duration, with the highest values observed during the ET period. Increases in RPE have previously occurred during ET (15—17) versus 90 min measures (10—14) (Harper et al., 2016a; Harper et al., 2016b; Harper et al., 2016d), with the d-RPE values for the current research being largely consistent. Values for ET were marginally, but consistently higher for RPE-L (15—17) versus RPE-B (15—16), corresponding to the descriptors 'hard' to 'very hard'. Higher RPE-L versus RPE-B, contradicts observations using other exercise modalities, such as intervals at 105% maximum aerobic speed (McEwan et al., 2018) and repeated sprint protocols (McLaren et al., 2020). The high d-RPE could reflect the high biomechanical demand of soccer-specific treadmill running (Page et al., 2015; Page et al., 2016; Page et al., 2019) and relate to decrements in the force-generating capacity of knee extensors (Goodall et al., 2017) or the reduced sprint ability during ET (Harper et al., 2016a; Harper et al., 2016b; Harper et al., 2016d; Kubayi & Toriola, 2018; Peñas et al., 2015; Russell et al., 2015b; Stevenson et al., 2017). Therefore, the increase in effort perceptions for local fatigue may corroborate the reductions in eccKF following ET observed in Chapter 5 and reiterates that players may utilise pacing approaches during match-play to minimise fatigue-induced acute injury occurrence.

The changes in average and peak HR and $\dot{V}O_2$ were inconsistently trivial and small across bouts. Considering the incremental nature of the changes in RPE-B across exercise, this suggests that this measure may not be a proxy for estimating systematic changes in pulmonary and cardiovascular outcomes. On the other hand, RPE-L progressively increased across exercise demonstrated uniformity with biomechanical measures of PlayerLoad™, thus suggesting that effort perceptions are a closer arbitrator for this construct. The cumulative manner of increase for all facets of d-RPE across 120 min of soccer is perhaps due to a mismatch between the genuine and template perceived exertion, caused by complex psychological mechanisms (Abbiss et al., 2015). Decreases in muscle activation have been ascribed to changes in central motor output for the purpose of counteracting peripheral fatigue during soccer-specific exercise (Marshall et al., 2014). Increases in peripheral biochemical markers influence nerve afferents via the transmission of metabolic information that then alter central motor drive to enable peripheral recovery (Amann, 2011; Sidhu et al., 2013). Evidence suggests that the regulation of exercise intensity appears mainly regulated by cerebral and physiological interactions that are perhaps explained by teleanticipatory processes (St Gibson et al., 2006), pacing awareness (Edwards & Polman, 2013), and/or the RPE template (Abbiss et al., 2015). These psychological aspects may have also influenced the results considering the inherent expectation that additional duration equates to incremental perceptions of effort. However, attempts to modulate these factors were made, including regulating each bout to ensure identical running speeds, temporal blinding of ET incorporation and recording effort perceptions in a counterbalanced manner. Therefore, considering that pacing is apparent during match-play, changes in d-RPE should be interpreted cautiously within such laboratory contexts.

Physiological and metabolic perturbations, and exacerbated perceptions of effort are apparent during ET. The evident challenges to systemic homeostasis and the additional mental demand that is seemingly posed by ET may have important recovery implications and is an integral consideration of athletic performance. While squad rotation may alleviate such concerns, recovery should be monitored to inform post-match recovery and training strategies as part of a holistic approach to athlete well-being.

8.4 THE IMPACT OF 120 MINUTES OF SOCCER-SPECIFIC EXERCISE ON RECOVERY

The transient biomechanical, physiological, and metabolic disturbances observed throughout the current thesis induces residual fatigue, characterised as reductions in performance during and in between matches (Andersson et al., 2008; Ascensão et al., 2008; Ispirlidis et al., 2008; Nedelec et al., 2014). The symptoms of post-match fatigue can persist for days after competition, hindering the recovery process (Nédélec et al., 2012). Therefore, considering that ET matches are often contested during fixture-congested tournaments (Julian et al., 2020a; Kołodziejczyk et al., 2021), and recovery appears to be impacted following 120 min of match-play (Russell et al., 2015b; Winder et al., 2018), there could be negative performance implications in subsequent matches in close proximity. Additionally, since the time course of recovery is influenced by the magnitude of fatigue experienced (Nédélec et al., 2012), the additional 30 min period of ET was investigated for its influence on recovery.

Competing in matches with < 96 hr inter-match period reduces distances covered at low and moderate speeds (Julian et al., 2020a), with limited recovery time between matches perceived as the primary external risk factor for injury in teams at the FIFA 2014 World Cup (McCall et al., 2015). Previous research also demonstrates that competing in 90 min matches is detrimental for muscle soreness, CMJ, isometric strength of the hamstrings and peak sprint speed in the 72-hr period thereafter (Nedelec et al., 2014). Throughout the thesis, the reported data has demonstrated that the ET period of soccer elicits negative changes to biomechanical efficiency (Chapter 4), further depletes endogenous fuel sources (Chapter 4) and reduces torque development capabilities (Chapter 5). Most practitioners in Chapter 6 believed that ET delays recovery and that practices should be adapted to reduce physical, physiological and metabolic stress, external load, exercise volume and duration and mental pressures. As a result, training loads and intensities were adapted by most respondents to account for the delayed time course of recovery that was perceived to occur. However, in Chapter 7, recovery of all functional and perceptual variables were not further impacted following ET versus 90 min of soccer-specific exercise. Creatine kinase activity, however, was significantly higher after the 120 min treadmill-based soccer simulation at 24 and 72 hr compared to corresponding measurements following the 90 min trial. Therefore, the current findings build on the literature by revealing that ET, at least based on the current results, does not affect recovery further than a typical 90 min duration, aside from CK activity. This may indicate a discrepancy between CK, and neuromuscular and perceptual markers of recovery. This observation also possibly reflects that CK is a highly sensitive marker relative to other proteins (Nédélec et al., 2012). Additionally, although under standardised conditions variability may be minimised, thus, providing a more reliable reference value for athletes, high interindividual variability exists for CK (Koch et al., 2014).

Previous studies involving 120 min free-running soccer-specific exercise protocols found that CK increased from pre (264 $\mu \cdot l^{-1}$) to (571 $\mu \cdot l^{-1}$) post ET (Harper et al., 2016d). In Chapter 7, increases from pre (109 $\mu \cdot L^{-1}$) to post 120 min (234 $\mu \cdot l^{-1}$) of treadmill-based soccer-specific exercise were also observed. Although the absolute CK values are largely heterogenous — perhaps given the high inter-individual variance for this marker (Paulsen et al., 2012; Urhausen & Kindermann, 2002) — the relative changes were similar between studies (pre-to-post increases of 117% [Harper et al., 2016d] vs 115% [Chapter 7]). A match-play study that proceeded to ET also found increases in CK from baseline (249 $\mu \cdot l^{-1}$) to 24 hr (835 $\mu \cdot l^{-1}$) and 48 hr (516 $\mu \cdot l^{-1}$) post exercise (Russell et al., 2015b). In Chapter 7, increases from baseline (109 $\mu \cdot L^{-1}$) to 24 (455 $\mu \cdot l^{-1}$) and 48 hr (302 $\mu \cdot l^{-1}$) were also identified. Therefore, the relative increases in the current study (317% [24 hr] and 117% [48 hr]) were somewhat comparable between Chapter 7 and Russell et al. (2015b) (236% [24 hr] and 107% [48 hr]). The magnitude of the increase was slightly greater in Chapter 7, perhaps due to the disparities in exercise mode (simulation vs match-play) and experimental controls (participants refrained from exercise 48 hr pre-trial vs an ecologically valid training and playing schedule). Interestingly, significantly higher CK activity was observed at 24 and 72 hr post 120 min, but not at 48 hr. However, CK was higher at 48 hr following the 120 min trial (301.6 ± 30.8 $\mu \cdot l^{-1}$) versus the corresponding time point following the 90 min trial (258.6 ± 28.9 $\mu \cdot l^{-1}$). Therefore, although this difference did not reach statistical significance (i.e., $p = 0.06$), the change represents a ~17% higher CK response following the 120 min trial. Thus, the lack of difference is likely related to statistical factors as opposed to the change being of no practical significance. Motorised treadmill-based protocols are designed to mechanistically replicate match scenarios, although are distinct in that players are required to complete the intensities set by the treadmill. Therefore, considering players in the match-play study may have self-paced in response to fatigue, thus impacting intensity and running output (Russell et al., 2015b), this may explain the slight discrepancy between changes in CK. However, the current protocol may be considered a close approximation of the muscle damage response associated with 120 min of match-play (Russell et al., 2015b). Therefore, the inferences drawn from the mechanistic data reported in Chapter 7 can be considered valid estimates of match-play.

In total, 88% and 82% of the surveyed practitioners in Chapter 6 agreed-to-very strongly agreed that ET delays recovery and that practices should be altered, respectively. Therefore, there is a clear disconnect between the findings of Chapter 7 and the perceptions and experiences of the practitioners in Chapter 6. It is not known the extent to which practices should be adapted following ET matches, nor whether recovery protocols should be modified based on CK values in isolation. In sport and exercise, CK is used as an indicator of cellular necrosis and tissue damage, with efflux linked to disruption of skeletal muscle components (Baird et al., 2012). Although debated extensively, elevations in CK are not linked to the typology of muscle fibres (Magal et al., 2010), but are largely representative of the degree of enzyme tissue activity specific for the individual (Baird et al., 2012). Baird et al. (2012) also highlighted that elevated CK after exercise might reflect a disturbance to muscle energy processes (i.e., expulsion of CK from the cytosol to maintain normal oxidative phosphorylation during prolonged exercise), so might not be representative of physical damage to muscle. Therefore, it is unclear the extent to which additional intracellular leakage of CK following ET represents damaged sarcomeres, membrane degradation and overall structural damage without muscle biopsies. However, since the functional measures were not exacerbated by ET, it appears that CK activity does not translate to the depletion of muscle energy availability and performance. Therefore, despite the higher CK levels following ET matches, there is limited evidence to suggest that practice should be adapted based on the current findings. Therefore, it appears that practitioners perceive that recovery is exacerbated following ET based on the assumption that the additional 30 min exercise duration induces additional residual fatigue and delays recovery. However, there remains a lack of robust scientific evidence to suggest that the additional activity associated with ET further delays recovery compared to a traditional 90 min match. The finding that practitioners individualised recovery for each player (Chapter 6) is an encouraging finding since there are differences in a soccer players recovery potential and altered recovery periods (Nédélec et al., 2012). As such, individualised recovery protocols should be devised following ET until further research is undertaken.

Despite an additional 30 min of fatiguing soccer-specific exercise, the absence of between-trial differences for most variables could be linked with the repeated bout effect (Verma et al., 2015). The repeated bout effect occurs when prior unaccustomed exercise is performed, and cellular adaptations occur to protect against further muscle damage (Kwiecien et al., 2020). All participants performed a session for full habituation a week before the initial main trial to enhance validity and reproducibility. This involved a full 120 min familiarisation trial of the treadmill-based protocol, which could have interfered with the acute and residual adaptive responses to the subsequent trial. In Chapter 7, a cross-over design was adopted to negate such influences, although in a real-world setting, players may not train for, nor be accustomed to competing for 120 min. For instance, as highlighted in Chapter 6, a high number of practitioners do not condition players for the additional demands of ET and training is likely geared towards preparing for matches of a 90 min duration. Therefore, the differences between 90- and 120-min matches under applied conditions may be more pronounced. Matches that require ET are typically followed by a 90 min match, although for the first time in history, a team in the knockout-phase of the 2018 FIFA World Cup competed in three consecutive ET matches (Kołodziejczyk et al., 2021). The four players that were monitored across the three 120 min matches covered twice as much high-speed distance (20–25 $km \cdot h^{-1}$ and >25 $km \cdot h^{-1}$) and double the number of sprints in the third versus the first ET period. This supports that repeated bout effects may occur if multiple ET matches are required and is reflective of the inherent variability between matches. However, to ensure that players are adequately conditioned for the additional 30 min period, practitioners are advised to prepare players before major tournaments for the prospect of ET. Furthermore, as the activity profile for the current treadmill-based soccer-specific protocol was standardised, participants were accustomed to the precise movement patterns upon completion of the familiarisation trial, whereas, between-match running profiles are entirely distinct (Gregson et al., 2010). As such, although evidence suggests that competing in matches that requires an ET period has detrimental effects on recovery (Russell et al., 2015b; Winder et al., 2018), the recovery response in the same group of players following 90- and 120-min matches has yet to be investigated. Therefore, this is an idea worthy of further examination.

Match-play is highly variable (Gregson et al., 2010), and thus, caution is advised when interpreting the recovery findings in Chapter 7, since the findings are not entirely ecologically valid. For instance, the non-multidirectional nature of treadmill running (Page et al., 2015) and absence of high-velocity unorthodox manoeuvres (cutting, twisting, turning and sideways running) that elicit high eccentric demands (Silva et al., 2018), may limit the extent to which players experienced muscle damage and performance decrements in the current thesis. However, in the literature, the recovery response to ET has solely been investigated utilising match-play studies, with small samples and a lack of control (Russell et al., 2015b; Winder et al., 2018). Therefore, the current thesis adds mechanistic value in that under strictly controlled conditions, recovery of functional indices is not further exacerbated by the ET period. However, a disconnect is apparent between the practitioner surveys on recovery and ET, and the functional and perceived recovery of the players assessed following the 120 min trial. The disassociation might be reflective of the simulation data and the applied field, since ET has shown to negatively impact functional recovery in the practical setting (Winder et al., 2018). It also appears logical to assume that the increased 30 min duration and subsequent volume of activity is sufficient to impose additional muscle damage and fatigue, with such debilitating effects influencing recovery. This notion could account for the survey perspectives, as little controlled research has been conducted on recovery following ET, and thus, practitioners may base their views on anecdotal experiences. However, the current research suggests that under tightly controlled conditions with few confounding variables, functional and perceived recovery is not influenced further following the completion of ET. Therefore, based on the conflicting findings between applied and lab-based research, practitioners are advised to use subjective observations (player familiarity and feedback) and scientific monitoring (quantification of key variables) to support their decisions for returning players to training and matches after an ET match. Further research using a variety of study designs (i.e., controlled and applied) is required. Given that ET is an important period in determining success at major soccer tournaments (Harper et al., 2016c), the increasing prevalence of 120 min matches (Kołodziejczyk et al., 2021) and the fixture congestion associated with contemporary competition schedules (Julian et al., 2020a), understanding the post-match fatigue and recovery responses to this additional timeframe is integral to enhancing performance in major tournaments.

8.5 PRACTICAL RECOMMENDATIONS

The series of studies conducted throughout this thesis offers practical recommendations and applied perspectives that may be of interest to practitioners. Based on the appraisal of the literature in Chapter 2, practitioners can adhere to the systematic review for insight into the current state of ET knowledge and utilise the relevant perspectives for their practice. Reductions in performance during ET are strongly evidenced with decreases in total, sprint and high-speed distance, as well as a reduced quantity of speed changes observed in the additional 30 min period (Chapter 2). Practitioners should use this information to their advantage and replace players that are identified as fatigued, at risk of injury or underperforming during ET. A contemporary rule change has been implemented by FIFA enabling a fourth substitute to occur during ET (Hills et al., 2020), which supports practitioners in managing fatigue and minimising load related injuries.

Chapter 4 and 5 identified that PlayerLoad™ increased as a function of exercise duration and continued to increase during the ET period. The increased PlayerLoad™ values identified during ET may imply that players are at a heightened susceptibility to injury (see section 4.1 for plausible injury aetiology) should they maintain the same running output in this additional period. This potentially elucidates that players 'self-pace' during ET to avoid injury, with the running performance metrics reducing as a consequence, which may have detrimental performance and success implications. However, elucidating the extent to which PlayerLoad™ data collected in the laboratory setting can be applied in real world contexts should be carefully considered on an individual and *ad hoc* basis. Therefore, practitioners should appraise the current PlayerLoad™ findings for their individual interpretations of load, injury, and fatigue during ET. The notion that PlayerLoad™ strategies changed into ET suggests that under the assumption that players maintain the same running output over 120 min, then a decrease in efficiency and a potential exacerbated injury risk would occur, theoretically, during the ET period in a match. This finding supports that players taper running output, subliminally, as a protective mechanism to minimise injury-risk, since maintaining the same intensity into ET appears to reduce efficiency and possibly exacerbate injury. However, since this concept was not directly investigated during match-play, some caution should be applied when transferring the findings to an actual match.

The soccer-specific exercise simulation deemed reliable in Chapter 4, could be utilised for practical purposes. Considered from a fatigue management perspective, the current protocol may be adopted for relevant 'top-up' training for partial match players (substitutes and those being replaced) (Hills et al., 2018). Another practical approach could be to utilise the treadmill for late-stage return-to-play rehabilitation, with such a training practice providing a progressive mechanical strain that closely replicates match-play (Silva et al., 2018). The treadmill design may be suitable for the omission of CoD elements associated with non-contact loading-related knee injuries (Dos'Santos et al., 2019). Therefore, for practitioners seeking reproducible exercise strategies that minimise recurrent load-related knee injuries, the present protocol may be an appealing form of exercise.

It appears players that fail to consume endogenous carbohydrate are susceptible to changes in energy metabolism pathways during ET, as evidenced in Chapter 4. The shift from glycolysis to lipolysis could be detrimental to the high-speed capabilities of soccer players during ET. Intermittent and high-speed exercise is largely dependent on muscle glycogen as a major fuel source to provide a high rate of ATP re-synthesis (Balsom et al., 1999). Therefore, it is key that practitioners optimise within-match opportunities for carbohydrate provision to offset the impact of fatigue during ET. To ensure that carbohydrate intake is maximised, a proactive approach towards ensuring player preferences are easily obtainable during the 5-min break prior to ET is integral for enhancing player engagement. The chapter examining changes in substrate utilisation across 120 min was designed as a proof-of-concept study to assess energy usage under circumstances where players fail to consume carbohydrate during competition. Although the acute benefits of carbohydrates on physical and skill performance are well-established (Foskett et al., 2008; Harper et al., 2016a; Russell & Kingsley, 2014), and contemporary professional soccer energy provision throughout 120 min is considered important (Harper et al., 2016c), it is possible that such nutritional intervention strategies are overlooked or not strictly implemented. Therefore, the current changes in substrate utilisation substantiate the need to priortise carbohydrate provision across 120-min, especially for lower playing levels with financial constraints, and can be utilised to ensure performance is optimised during ET.

The findings in Chapter 5 indicate that the fatigue experienced during ET is influenced by a complex interaction of both peripheral and central factors. Central fatigue manifested in the loss of neural drive to the rectus femoris, resulting in a decrease in motor unit recruitment during ET. The development of peripheral fatigue was observed through muscle contractile deficits and the reductions in peak torque of the eccKF. Considering that fatigue-induced deficits in hamstring strength are observed during the latter stages of 90-min durations (Cohen et al., 2015; Marshall et al., 2014; Small et al., 2010), and fatigue is a risk factor for injury (McCall et al., 2014), it seems reasonable to speculate that the strength deficits are likely to increase injury susceptibility during ET. However, this finding might need to be reviewed against the isokinetic dynamometer's functional relevance to movement. For example, quantifying losses in eccentric torque with an isolated limb at velocities lesser than the speeds achieved whilst sprinting (Eustace et al., 2017; Nedergaard et al., 2014; Page & Greig, 2020), might not represent the actions performed during match-play. Furthermore, the different mechanical factors between treadmill and overground running (e.g., step frequency, length, contact and flight times, peak knee abduction and extension angles upon ground contract) (Van Hooren et al., 2019) may have influenced the eccentric strength characteristics of the limb and subsequent injury susceptibility. However, since match-play contains additional movements (CoD, twists, turns, backwards and sideways movements), it is likely that the response to the current treadmill-based protocol was a conservative proxy, thus, strength losses might be increasingly likely during match-play. It has been demonstrated that eccentric strength training interventions decrease hamstring strain susceptibility in soccer players (Arnason et al., 2008; Petersen et al., 2011; Van Beijsterveldt et al., 2013). Players should be screened for eccentric hamstring deficits, and proactive and pragmatic injury prevention programmes should be implemented into training microcycles that develop eccentric hamstring torque at greater muscle lengths and increase player resistance to fatigue-induced strength deficits. This should be prioritised before major tournaments that involve matches that have the capacity to proceed to ET.

The findings in Chapter 7 demonstrate that although CK indices are higher following 120 min of soccer-specific exercise, functional measures of recovery are not exacerbated by the ET period versus 90-min markers. This suggests that a large disassociation exists between the CK response and functional variables. Therefore, according to the current data, it appears that recovery practices should not be adapted, and training can resume as normal following ET matches like traditional 90 min matches. That said, inter-individual variances in recovery potential are apparent (Nédélec et al., 2012), and as such, recovery protocols following ET matches should be individualised as opposed to generic for the entire team. Individual players experiencing residual fatigue following ET should be identified using physical, physiological, and subjective assessments. However, if players are identified as needing an additional 'rest', then practitioners may need to consult the head coach to ensure training loads are sufficient to maintain optimal conditioning. Careful periodisation of training is particularly key during fixture dense tournaments to ensure players are adequately conditioned for optimal performance and a reduced injury incidence during ET.

A brief overview of the practical recommendations is provided below:

- Reductions in total and sprint distances, as well as accelerations and decelerations occur during ET, possibly due to fatigue or self-pacing. Players that are unable to maintain their running output during ET should be identified and replaced where contemporary competition rules permit the introduction of an additional substitution during this additional period of match-play.
- PlayerLoad™ increases during ET when measured across periods of standardised soccer-specific running activity, thus, indicating that players are unable to maintain efficiency across 120 min. These results also imply that players employ pacing strategies as opposed to being unable to maintain running output due to fatigue. Practitioners may profit from these findings through use of their bespoke interpretations and applications in line with their team's practices.
- The current treadmill-based soccer-specific simulation can be used as a reliable exercise modality for the evaluation of fatigue responses across 120 min. Researchers may use the protocol to simulate ET matches for investigations into the efficacy of nutritional interventions, and the effect of environmental stressors on physical

performance and physiological responses. The protocol may be also adopted in the practical setting for additional training for squad players and rehabilitation purposes for those returning from injury.

- A switch in the metabolic pathway occurs during ET towards the direction of lipolysis in players that fail to consume within-match carbohydrate. Carbohydrate provision is advised in the 5 min break prior to ET. In order to optimise engagement, practitioners should consult players prior to matches that have the potential to proceed to ET to ensure preferred carbohydrate sources are readily available.
- There appears to be a fatigue-induced impairment of torque generating capacity in the knee flexors during eccentric peak torque evaluations following 120 min of soccer-specific exercise. This could possibly increase hamstring injury propensity during ET. Preventive training programmes should target the development of eccentric hamstring strength to minimise the risk of hamstring strain injuries during ET.
- Functional and subjective markers of recovery appear to be similar following both 90 and 120 min of soccer-specific exercise. Therefore, the current data provide evidence to suggest that there is little requirement for players to have an additional rest following ET matches and training should resume as normal. However, it is advised that practitioners base their decision of whether players should return to training on individual fatigue assessments.

The above practical applications must be carefully interpreted and contextualised on the basis that the findings in the current thesis may present more mechanistic than applied value. Although logistical challenges prevented the inclusion of various assessments within the experimental chapters, incorporating such measures would have inherently increased the application of the research. For instance, many studies have demonstrated that soccer-specific exercise negatively influences single- (Ascensão et al., 2008; Magalhães et al., 2010) and repeated-sprint capacity (Krustrup et al., 2006; Mohr et al., 2004), with sprint actions often leading to decisive moments in elite soccer match-play (Faude et al., 2012). Reductions in sprint ability have also been observed following 120-min of soccer-specific exercise (Harper et al., 2016a; Harper et al., 2016b; Harper et al., 2016d; Stevenson et al., 2017) and match-play (Peñas et al., 2015; Russell et al., 2015b). Therefore, given that sprinting is a crucial component of soccer and fatigue can manifest through an impeded sprint capacity (sprint speed and number of sprints), evaluating the changes in sprint capabilities through both single and repeated protocols may have enhanced the implementation of the current findings within the applied soccer environment. Research has also shown that skill acquisition (passing, dribbling, and shooting) is negatively impacted in response to 120-min of soccer-specific exercise (Harper et al., 2016d; Harper et al., 2014; Stevenson et al., 2017). As such, given the importance of technical components in soccer match-play (Rampinini et al., 2009), measuring the changes in skill performance in response to 120-min would have improved the application of the current findings. However, incorporating skill tasks within the design of a soccer-specific protocol may prove complex for technically incapable cohorts, which can jeopardise the physical impetus (Russell & Kingsley, 2011). Therefore, considering the treadmill-based design, the technical assessments would have been undertaken within the passive intervals, thus, perhaps invalidating the fatigue response. Therefore, a decision was taken not to include skill actions within the design as the fatigue response to the soccer-specific protocol was priortised. Furthermore, assessing technical components necessitates a vast area, with the current research not feasibly able to accommodate access to large laboratory spaces or sports halls.

8.6 METHDOLOGICAL LIMITIATIONS AND FUTURE RESEARCH AVENUES

The novel studies conducted throughout this thesis present interesting nuances and future perspectives, but there are several methodological limitations that should be considered alongside interpretation of the findings. This section will highlight the fundamental design and methodological limitations present throughout the thesis, while discussing avenues worthy of future exploration.

Several research studies should be conducted to expand the knowledge gained from some of the individual chapters within this thesis. In Chapter 4, accumulated fatigue manifested as a change in RER, thus, implying that endogenous carbohydrate is further depleted in response to prolonged soccer-specific exercise. This seems logical as a progressive depletion in glycogen content in muscle fibres has been observed across a 90-min match (Krustrup et al., 2006). However, using solely indirect calorimetry with no other technique may prove incomprehensive to ascertain accurate conclusions. Accompanying ventilatory assessments with direct methods to examine glycogen concentrations such as invasive muscle biopsy procedures may enhance understanding of energy metabolism during ET.

In Chapter 5, a fundamental design limitation was that isokinetic peak torque assessments were performed solely at baseline and after ET, with no measures taken in the intervening periods. As such, the interpretation of the changes is solely limited to pre-exercise as opposed to HT, full-time or at other time points throughout the trial. However, given that additional eccentric and concentric isokinetic contractions may have been additive to and potentially invalidated the fatigue response, such measurement timing was deemed appropriate. On the other hand, though it would have been ideal to measure peak torque at each 15-min interval, the time burden associated with obtaining such measures could have potentially allowed time for fatigue induced by the protocol to dissipate. As such, the validity of the activity profile was prioritised rather than taking measures at each 15-min period. The information of a single peak torque measure may also be a limitation with no information as to which angle deficits are pronounced. Contemporary research suggests that the torque angle profile can provide a more detailed understanding of injury vulnerability by recording the strength-angle curve across the entire ~90º motion (Page & Greig, 2020). Furthermore, slower rates of force development have been observed in individuals with hamstring history (Opar et al., 2013) and faster rates shift the optimum torque angle towards longer muscle lengths (Timmins et al., 2016b). Therefore, the rate of torque development and the capacity to generate maximal voluntary activation in the early phase of a rapid movement is considered functionally more relevant than a maximal torque measure due to the speed of muscle activation being integral for performing postural corrections during running and landing (Buckthorpe & Roi, 2017). Forward thinking sports scientists and researchers should assess the angle of peak torque and rate of torque development following ET. From an injury prevention perspective, this would enable researchers to identify which angle peak torque losses occur and whether rate of force development id adequate to correct acute postural deficits to avoid injury. Such information would help address these modifiable risk factors for injury elicited during ET.

It is accepted that the survey responses collated in Chapter 6 correspond only to the practitioners responsible for recovery practice implementation with the largest proportion of respondents being sport scientists. Thus, although the high return rate of this population may indicate that sports scientists play a prominent role in recovery, no inferential statistics were performed to compare the perceptions of different stakeholders (Nosek et al., 2021; Weston, 2018). Future research should statistically assess the varying interests of key stakeholders (e.g., managers, medical staff, and players) in relation to implementation of recovery practices following ET matches. It must also be noted that when approached to complete the survey, practitioners were informed about the topic of the investigation in advance of completion. Therefore, the results may be susceptive to sampling error as the practitioners that responded may have had been more invested in the ET period versus the entire representative sample of professional soccer practitioners.

Another highly supported area of future research from the survey data were evaluating changes in acute injury-risk in response to ET matches. Previous evidence suggests there is an increased injury incidence during ET (Aoki et al., 2012), although these data are outdated (1993 to 2007) and are epidemiological observations based on contact injury. The acute (i.e., one-week) and chronic (four weeks) loading pathways to injury have been investigated (Windt & Gabbett, 2017), although the understanding of immediate within-match non-contact injury aetiology is yet to be elucidated. Contemporary biomechanical models of injury causation should be developed to enable researchers to assess whether the acute loading patterns and biomechanical stress encountered during ET exceeds the tolerance of the mechanical properties of the tissue for individual players and whether injury is likely to ensue as a result. This may also be appropriate for evaluating whether players are at an increased susceptibility to injury in training sessions and matches following a game that has proceeded to ET.

Small sample sizes of the studies present within the individual chapters are a fundamental limitation of this thesis. From a statistical perspective, insufficient sample sizes can inevitably lead to an underpowered study (Ramirez-Campillo et al., 2020), thus, reducing the prospects of detecting an effect (Drust et al., 2007). It appears that sports science research is replete with underpowered studies, which is demonstrated by the low number of submissions (~10% of the sample of papers selected) to the *Journal of Sports Sciences* that contained a formal *a priori* sample size estimation (Abt et al., 2020). This is likely a function of the logistical burden of recruiting specialised populations and the large time and effort commitment associated with exercise testing. Nonetheless, *a priori* power analyses were performed to ensure that the sample sizes were adequate to detect medium or large effects for the experimental chapters. However, the sample size estimations were conducted under the presumption that sphericity associated with repeated measures designs (i.e., highly susceptible to the violation of the assumption of sphericity) would be met (i.e., not violated). Likewise, these *a priori* estimates are innately abstract as they are calculated based on presumptions that are incapable of being tested until the data are collected. Furthermore, it must be noted that the ES criteria employed for the power analyses were not conservative estimates, such that large ESs were used. A decision was taken by the lead researcher to adopt a large ES based on the impracticalities associated with the excessive number of participants required to detect small and medium ES. The variability in the primary outcome variable can also influence sample size estimations (Batterham & Atkinson, 2005). Therefore, although the experimental chapters were 'adequately powered' to detect a difference, the fundamental flaws associated with sample size estimations may reduce the chances of a statistically significant finding, assuming such a difference truly exists (Hopkins, 2000). For this reason, some of the changes may be based on conservative estimates, and thus, should be considered when interpreting the null findings in the individual chapters, particularly where changes neared significance.

The results from the experimental chapters may be specific to the discrete population of players and experimental protocols that were used throughout the thesis. Therefore, generalising the findings from university-standard and semi-professional players to other athletic populations may be difficult. Accessing elite populations is challenging; however, the mean $\dot{V}O_{2max}$ values for the participants in the experimental chapters were between 57 and 59 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$. These values are largely comparable to elite soccer populations (~62–64 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) (Tønnessen et al., 2013), and thus, the fitness levels and conditioning of the participants recruited for the current thesis may be somewhat comparable to elite players. Furthermore, the YYIET level 1 and 2 tests are sensitive for discriminating performance across various competitive levels, with these tests shown to significantly correlate with $\dot{V}O2_{max}$. However, perhaps a better indication of the ability to perform repeated high-speed running actions (Bangsbo et al., 2008). Therefore, based on the YYIET level 2 equation ($\dot{V}O2_{max}$ (ml·kg^{-1}·min^{-1}) = IR2 distance (m) x 0.0136 + 45.3), the current population (860 —1000 m) would have theoretically covered ~220 m less than the elite soccer players in the Tønnessen et al. (2013) study (1220—1370 m). Therefore, although efforts were made to minimise this issue, the results may need to be interpreted with caution before extrapolating to the wider athletic population. It must also be noted that the ET period is required in female soccer (Williams et al., 2019), thus, because of the physiological sex differences (Julian et al., 2020b; McNulty et al., 2020), the current findings are not able to be easily transferred to this population. Therefore, the performance and physiological responses of competing in ET matches in female soccer players should be assessed. Likewise, there is considerable differences in biological maturity and physical/physiological performance in youth populations (Itoh & Hirose, 2020). For this reason, caution must be applied when translating these findings, and as such, the effects of ET on performance and recovery in youth players should be investigated.

The approach to study design and the analysis of subsequent data can ultimately influence study outcomes (Brooks & Fuller, 2006). Previous researchers have examined changes in soccer match intensities across each half (Di Salvo et al., 2009; Rampinini et al., 2007; Rivilla-García et al., 2019) and individual 15 min bouts of activity (Bradley et al., 2009; Mohr et al., 2003; Russell et al., 2011a). However, critics have argued that such broad data categorisation may reduce sensitivity to detect within match changes, fail to depict participant variation and could lead to misinterpretations (Weston et al., 2011b). It is also likely that 'regression toward the mean' may occur when analysing data over such extensive periods. This statistical phenomenon relates to the tendency for the more extreme values from the sample mean in the first observation to be closer to the mean on subsequent occasions (Merz et al., 2021). In light of the above, the categorisation of 15-min periods for the current thesis may be considered a limitation. This approach was taken to provide comparisons between six equal periods throughout 90 min to each of the ET halves in parity with previous ET observations (Harper et al., 2016d; Peñas et al., 2015; Russell et al., 2015b; Winder et al., 2018). However, research designs that classify data into 5-min periods have provided between timepoint comparisons that are more sensitive to detect statistical changes in intensity (Weston et al., 2011b). Therefore, the studies in this thesis may have been improved through accurately determining the precise timepoint at which physical performance reductions occurred during ET had the data been dissected into 5-min periods.

The current thesis develops experimental and mechanistic knowledge of the biomechanical, physiological and recovery responses to the ET period of soccer. However, the laboratory setting in which the research was conducted throughout the experimental chapters limits the ecological validity of the results. Ecological validity relates to the extent to which observed behaviours in the laboratory environment can be applied in real-word contexts (Schmuckler, 2001). In the context of the present thesis, this notion relates principally to the motorised treadmill-based protocol utilised to assess the various facets of ET. Using treadmill-based protocols to replicate soccer match-play may lack ecological validity and limit the generlisability of the findings (Harper et al., 2016d). However, such models are pertinent for when a controlled and reproducible soccer-specific exercise stimulus is required (Greig et al., 2006; Page et al., 2015). Therefore, although there exists a reliable 120-min free-running simulation (Harper et al., 2016d), the current protocol is the sole treadmill variant that can be considered a reliable representation of ET match-play.

The velocity profile of the protocol was based upon average data derived from the movement strategies of a range of elite outfield soccer players across various positions. However, the validity of the ET portion of the protocol remains largely unknown given the same activity profile was applied for the two additional 15 min bouts of ET. These interpretations could thus be erroneous given that decrements in physical performance during the ET period have been observed in competition (Peñas et al., 2015; Russell et al., 2015b). Therefore, it is possible that players cover less distance, and perform fewer sprints, high-speed actions, accelerations, and decelerations during ET, although this is not reflected in the current activity profile. However, a stance was taken to remain with the initial fixed bouts of running activity to provide assurance that within-exercise changes observed were due to a reduced physical capacity, rather than self-pacing tactics or player motivation. This enabled direct comparisons of equal and standardised running activity between the two ET bouts and 15 min bouts performed throughout the 90 min duration. Furthermore, during the protocol the players covered similar distances and performed a consistent number of sprints with 120-min match-play observations (Russell et al., 2015b; Winder et al., 2018). Therefore, the current treadmill-based simulation may be utilised as a reproducible exercise strategy for assessing fatigue-induced changes in performance under tightly controlled conditions.

The current protocol may be used to address some of the practitioners' suggestions for future research in Chapter 6. The most prevalent recommendation for future research was tracking the physical and physiological response following ET. Accordingly, the experimental study in Chapter 7 was carried out to assess the physical and physiological response acutely and in the days following 120 min of soccer-specific exercise. Investigating nutritional strategies to accelerate recovery was recognised as the second most endorsed area of future research.

Several nutritional interventions utilised to accelerate recovery from varying exercise modes have been examined, such as, protein, carbohydrate, and functional foods (omega-3 FFA, curcumin, tart cherry, beetroot, tomato, pomegranate, blueberry juice and cocoa flavanols) (Corr et al., 2020; Heaton et al., 2017; Nédélec et al., 2013; Ranchordas et al., 2017). The efficacy of the above nutritional strategies in enhancing recovery following 120-min matches should be explored.

An aspect identified by some practitioners as warranting further consideration was assessment of the effects of non-nutritional interventions on recovery. Therefore, the effectiveness of sleep (Nédélec et al., 2015), massage (Poppendieck et al., 2016), compression garments (da Silva et al., 2018), cold-water (Machado et al., 2016) and hot treatments (McGorm et al., 2018) on recovery should be investigated following ET matches. Other lines of future research enquiry derived from the survey feedback in Chapter 6 were the cognitive demands of ET, the effects of travel modality and overnight stay on recovery following ET, and the impact of ET on performance in the following match. Mental fatigue may contribute to physical fatigue and subsequent performance reductions identified during and following soccer match-play (Smith et al., 2018). Thereby, considering ET matches normally occur following an arduous season, assessing whether the ET period exacerbates cognitive processes and results in chronic fatigue is required. Away match logistics (travel and/or staying in unfamiliar environments) may impede recovery (Fowler et al., 2014), particularly following matches that proceed to ET, thus, this study idea should also be explored. The impact of ET matches on subsequent performance in 90-min matches has been investigated (Winder et al., 2018). However, to eliminate the many situational variables associated with match-play (Lago et al., 2010), soccer-specific exercise protocols should be used to assess the impact of ET on subsequent performance.

8.7 SUMMARY

In conclusion, through the series of studies (review article, empirical observation and experimental research) conducted throughout the current thesis, the findings indicate that, 1) physical performance (less total and sprint distances) is reduced during ET, but there are a paucity of experimental mechanistic investigations that have assessed the biomechanical and physiological aetiology of fatigue, and the recovery response following ET, 2) the cause of fatigue during ET appears to be both of a biomechanical (reductions in movement efficiency) and physiological nature (shifts in substrate utilisation), 3) fatigue during ET might be linked with both central (reduced muscle activation) and peripheral (deficits in strength) factors, 4) applied practitioners largely modify recovery strategies in response to the additional 30 min period and are largely in favour of future research on recovery and ET, and 5) despite an elevated CK response, ET does not further impede recovery over and above 90 min of soccer-specific activity.

The current thesis merges distinct methodological approaches and disciplines (e.g., biomechanics and physiology) to provide a holistic understanding of soccer performance and recovery in the pursuit to further knowledge of the ET period. Original data are presented throughout the thesis together with novel perspectives that are ultimately designed to inform practice and generate further lines of research enquiry. In terms of application, the scope of the current data supports that ET exacerbates fatigue and practical solutions are offered to minimise the occurrence and influence of fatigue on injury and performance. The modern day applied soccer practitioner is responsible for ensuring that performance and recovery practices are evidence-led via methodical application of scientific research. With the clear deficit of ET research in contrast to the wealth of literature appropriate for 90 min durations, practitioners are challenged with the uncertainty of whether to remain with normal approaches to performance and recovery or use anecdotal experiences to inform ET practice. This lack of understanding may be detrimental for practice and could lead to inadequate conditioning, underperformance, injury occurrence or suboptimal recovery in response to ET. Therefore, investigations across the full spectrum of methodology are necessitated to elucidate the physical, physiological, technical, and cognitive demands of ET. For instance, although match-play studies may accelerate the translation of research and are required, furtherance of research conducted in laboratory environments should be embraced positively to collate a well-informed canon of evidence that comprehensively enhances the understanding of ET.

Matches that progress to ET are often played amid dense fixture periods (i.e., in the knockout-phase matches of international competitions or an ET midweek match between two weekend fixtures), with the repetition of training and matches in a short period having harmful implications (Julian et al., 2020a). There is an increasing occurrence of fixture congestion in contemporary soccer schedules (Carling et al., 2015; Julian et al., 2020a; Page et al., 2019); thus, knowledge on whether players encounter additional fatigue and delayed recovery in response to ET has become increasingly consequential. Since the first published ET works in 2014 (Harper et al., 2014), the research movement has been relatively modest. The overall quality of the ET literature is not inadequate, but rather the shortage of scientific evidence versus the knowledge pertinent for 90 min approaches creates excessive uncertainty for the applied practitioner and speculation over certain facets of the additional period. An approach must be taken to address the dearth of evidence moving forward to ensure that optimal practice is achieved. To facilitate this process, it is imperative that practitioners and researchers liaise closely to ensure research is apposite and genuinely beneficial.

It was once said by the great Bobby Robson that ‘the first 90 minutes of the match are the most important’. The time has come to embrace change in the modern era and start to give extra-time the ***extra*** attention it demands.

9.0 APPENDICES

9.1 Appendix 1 – Example of institutional ethical approval

From: SHUM Research Ethics
Sent: 15 November 2018 14:36
To: Adam Field (Researcher) <Adam.Field@hud.ac.uk>
Cc: Liam Harper <L.Harper@hud.ac.uk>; Matthew Haines <M.Haines@hud.ac.uk>; Steve Lui <S.Lui@hud.ac.uk>
Subject: SREP Application - Adam Field (PhD) - APPROVED - An assessment of the reliability of responses during 120 minutes of a contemporary soccer-specific protocol (SREP/2018/086)

Dear Adam,

The reviewers of your SREP Application as detailed above have confirmed that you have addressed the issues raised to their satisfaction and your Application has now been **approved outright.**

With best wishes for the success of your research project.

Regards,

Kirsty
(on behalf of SREP)

Kirsty Thomson
Research Administrator
: 01484 471156
: hhs_srep@hud.ac.uk
: www.hud.ac.uk

School of Human and Health Sciences Research & Enterprise Admin Office
Ramsden Building – R1/17
University of Huddersfield | Queensgate | Huddersfield | HD1 3DH

9.2 Appendix 2 – Example participant information sheet

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Assessing the reliability of soccer exercise; equivalent of two 120 minute matches (90-minutes + Extra-time) using a treadmill.

INFORMATION SHEET

You are being invited to take part in a study investigating the reliability of responses during 120 min of soccer-specific exercise. Before you decide to take part it is important that you understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with the investigator if you wish. Please do not hesitate to ask if there is anything that is not clear or if you would like more information.

What is the study about?
This project is designed to investigate the reliability of responses following a soccer protocol on the treadmill such as jump height (CMJ), blood markers (blood lactate and glucose), your perception of how hard you're working (RPE), acceleration changes (using a GPS system) and heart rate. Research has been conducted previously on the reliability of the aforementioned responses during a 120 min field-based protocol, although, this study will investigate the same responses during a 120 min treadmill- based soccer protocol. If the responses to this soccer- specific protocol prove to be reliable, this will potentially inform future research, enabling more valid and reliable conclusions to be drawn from similar research. This research may also be used to inform practitioners working within soccer of how the body responds to 120 minutes (Extra-time) differently to how it responds to 90-minutes of soccer exercise. Therefore, this study aims to assess the reliability of responses during a contemporary 120 min treadmill- based soccer-specific protocol.

Why I have been approached?
You have been asked to participate because you currently play football and have been playing for two years or more.

Do I have to take part?
It is your decision whether or not you take part. If you decide to take part you will be asked to sign a consent form, and you will be free to withdraw at any time and without giving a reason. Should you wish to not take part in the study or withdraw at any point, this will not affect your place in the university football team or your position at the university.

What will I need to do?
If you agree to take part in the research you will be asked to visit the University of Huddersfield exercise physiology labs to undergo a screening process. During the screening process your eligibility to participate will be assessed. If you choose to participate you will then undergo tests that will assess your aerobic capacity and body composition. The aerobic test will involve a VO_{2max} test that involves running on a treadmill with a mask on in order to estimate how fit you are. The body composition test will use the skin fold method whereby we will use skinfold callipers at specific sites around the body to estimate body fat percetage. Following this initial testing day you will be required to come to the labs three times. Visit one will involve you being fully habituated with equipment and the 120 min treadmill-based, football-specific protocol. Your next two visits will involve you completing 120 min of the protocol, but this time you will also be asked to provide a urine sample pre- and post-exercise, as well as provide a small amount of blood from your finger 11 times across the course of each visit. You will also be asked to consume a meal 90 minutes prior to exercising, in which a heart rate monitor and a Global Positioning System unit will be worn. In total you will visit the lab **4 times**.

Will my identity be disclosed?
All information disclosed from the study will be kept confidential and protected by the use of a pseudonym and storing data in password protected files on a secure computer.

What will happen to the information?
All information collected from you during this research will be kept secure and any identifying material, such as names will be removed in order to ensure anonymity. It is anticipated that the research may, at some point, be published in a journal or report. However, should this happen, your anonymity will be ensured, although it may be necessary to use your words in the presentation of the findings and your permission for this is included in the consent form.

Who can I contact for further information?
If you require any further information about the research, please contact Mr Adam Field (Adam.Field@hud.ac.uk) or Dr Liam harper (l.harper@hud.ac.uk).

Version 1: dated 03:10:18

9.3 Appendix 3 – Example informed consent document

University of HUDDERSFIELD
Inspiring tomorrow's professionals

CONSENT FORM

The effects of the extra-time period of football on recovery

It is important that you read, understand and sign the consent form. Your contribution to this research is entirely voluntary and you are not obliged in any way to participate, if you require any further details please contact Mr Adam Field (Adam.Field@hud.ac.uk) or Dr Liam Harper (l.harper@hud.ac.uk).

- I have been fully informed of the nature and aims of this research as outlined in the participant information sheet (Version 1: dated 19/09/19). ☐
- I consent to taking part in the research project. ☐
- I understand that I have the right to withdraw from the research at any time without giving any reason. ☐
- I understand that the information collected will be kept in secure conditions for a period of 10 years at the University of Huddersfield. ☐
- I understand that no person other than the researcher/s and facilitator/s will have access to the information provided. ☐
- I understand that my identity will be protected by the use of pseudonym in the report and that no written information that could lead to my being identified will be included in any report. ☐
- I consent for the findings of this study to be published in academic journals or conference proceedings ☐

If you are satisfied that you understand the information and are happy to take part in this project, please put a tick in the box aligned to each sentence and print and sign overleaf.

Signature of Participant: ______________	Signature of Researcher: ______________
Print: ______________	Print: ______________
Date: ______________	Date: ______________

(one copy to be retained by Participant / one copy to be retained by Researcher)

9.4 Appendix 4 – Example risk assessment

UNIVERSITY OF HUDDERSFIELD

GENERAL HEALTH AND SAFETY RISK ASSESSMENT FORM

Description of activity: Finger prick/ venous blood sampling			
Location: RB17, RB18 & RG14	**Assessment by: Adam Field**	**Assessment date: 05/05/19**	**Review date: 12 months**

GENERIC RISK MANAGEMENT MEASURES
Health and safety risk management measures appropriate to all aspects of the activity being assessed
Puncturing skin when taking capillary blood samples. • Gloves

SPECIFIC ASPECT OF ACTIVITY:			
Hazards identified	**Risks to health and safety**	**People at risk**	**Health and safety risk management measures**
Biological hazard from interaction with human blood samples (unscreened for blood borne disease).	Risks - rare that this would happen but should the phlebotomist be exposed to a contaminated sample then a permanent infection such as HIV) would occur (low risk). Cross contamination.	Phlebotomist.	• Researcher will have correct phlebotomy training. • Any open wounds must be covered during procedure. • One-time use of safety lancets. • Dispose of sharps instruments in sharps bins immediately after use and store in a safe place until collected • Wash hands thoroughly, both prior and following blood sample
	Needle stick injury.	Phlebotomist	• Bleeding should be encouraged under running water for one minute. • Apply pressure and perform first aid.
	<u>Reflotron safety hazards</u>: Electricity / electric Slips and trips / cables. Entrapment.	Phlebotomist / all in vicinity.	• Adhere to local A + S codes of practice. • Report any instrument faulty or malfunctions and remove from service. • Take care opening winged table/trolley.

Version: May 2019

9.5 Appendix 5 – Food record diary and instructions

CONFIDENTIAL

Participant Number: …….
Trial Number: …….

FOOD DIARY

Please record everything you eat and drink for the 24 hours prior to your trial, as well as the day of your trial, and up until your final recovery measure (~72 hours post-trial). Instructions and examples are given inside.

Information about your diet will be treated in confidence.

If you have any problems, please contact Adam Field (adam.field@hud.ac.uk)

Division of Sport, Exercise and Nutrition Sciences
School of Human and Health Sciences
University of Huddersfield
Huddersfield
HD1 3DH

INSTRUCTION FOR USING THE FOOD DIARY

Everything that you eat and drink over the course of the day should be weighed and the weight and type of food or drink recorded.

For solid foods, the food should be placed on the scale on a plate or container. The plate or container must be weighed empty first and the scales can then be zeroed. Each item of food can then be added to the plate and weighed individually, returning the scales to zero between each item.

e.g.	Plate	150g zero scale
	Roast Beef	100g zero scale
	Potato	150g zero scale
	Gravy	30g zero scale

For drinks, a cup or glass must first be weighed and then the scale can be returned to zero and the drink added. Please remember to record separately the weight of tea, milk and sugar put into a drink.

Do not forget to weigh and record second helpings and between meal snacks.

Any leftovers (e.g. apple cores) should also be weighted and recorded in the leftovers column.

Eating Out – Most people eat foods away from home each day, please do not forget to record these. Take your diary and scales with you wherever it is possible. If this is too inconvenient just record the type of food eaten with an estimated weight – but please say when a weight has been estimated.

Most snack foods will have the weight of the food on the packet, so they do no need weighing if you eat the whole packet yourself.

Names and descriptions of foods should be as detailed as possible, including the brand name and any other information available.

e.g. Cheese – is insufficient information.
Cheese, cheddar (Cathedral City) 20g – is sufficient information.

Start a new page in your diary for each day and record each item on a separate line. Record the time of day in the first column of each line.
e.g. 10:30 am McVities Digestive Biscuits (2) 50g

The space provided at the foot of each page for general comments is for you to give any further information about your diet and your training/activity for that day.

e.g. Missed lunch due to stomach pains

DAY 1 (DAY BEFORE TRIAL)
Date: / /

Please use a separate line for each item eaten; write in weight of plate; leave a line between different 'plate' entries.

A	B		C	D	E	F	**Office Use**
Time	Food eaten		Brand name of each item (except fresh food)	Full description of each item including: -whether fresh, frozen, dried, canned -cooked: boiled, grilled, fried, roasted. -what type of fat food fried in	Weight Served	Weight of Leftovers	Actual Weight
am/pm	home	away			(gms)	(gms)	(gms)

GENERAL COMMENTS:

9.6 Appendix 6 – Borg 15-point (6–20) rating of perceived exertion scale (Borg, 1988)

RATING OF PERCEIVED EXERTION

6	NO EXERTION AT ALL
7	
8	EXTREMELY LIGHT
9	VERY LIGHT
10	
11	LIGHT
12	
13	SOMEWHAT HARD
14	
15	HARD
16	
17	VERY HARD
18	
19	EXTREMELY HARD
20	MAXIMAL EXERTION

9.7 Appendix 7 – Visual analogue scale

University of
HUDDERSFIELD

Please mark a vertical line below rating the level of muscle soreness you are experiencing throughout your body.

No pain

Unbearably painful

9.8 Appendix 8 – Online survey questions

Supplementary materials

Survey questions:

Q1. Having read the previous participant section, do you wish to take part in this survey?

- I am 18 years old (or above) and wish to take part in this survey I do not wish to take part in this survey
- I do not wish to take part in the survey

Q2. Please create a unique 6-digit ID. This will comprise of the last two numbers of your date of birth, the last two digits of your postcode, and the last two digits of your phone number.

For example, DOB: 12/10/1992, postcode: HD6 2HR, phone number: 07730437556.

Unique ID: 92HR56.

Please remember your unique I.D as this will allow you to withdraw your data from the study up until the time and date specified below:

Please email Adam.Field@hud.ac.uk or L.Harper@hud.ac.uk or should you wish to withdraw your data from the survey. This will allow you to contact the researcher to withdraw your responses. It must be noted that anonymity will be compromised when contacting the researcher, although your data will be deleted. You have until 00:00 hrs on 31st May 2020 to withdraw data.

Q3. What is your job title?

- Head Coach Assistant
- Coach Strength and Conditioning Coach
- Fitness Coach
- Sports Scientist
- Performance Analyst
- Nutritionist
- Physiotherapist
- Sports Therapist
- Exercise Physiologist
- Head of Science and Medicine
- Team Doctor
- Other (please specify)

Q4. At which level of football do your team currently compete?

- International
- Professional
- Semi-professional
- Other (Please specify)

Q4a. Please state on which continent the country is located.

Q5. How much do you agree with the following statement?

‘In my experience, extra-time negatively impacts recovery when compared to a 90 min match'

- Very strongly agree
- Strongly agree
- Agree
- Neither agree nor disagree
- Disagree
- Strongly disagree
- Very strongly disagree

Q6a. How much do you agree with the following statement?

'Recovery following a match that requires extra-time, should be adapted when compared with a typical 90 minute match'

- Very strongly agree
- Strongly agree
- Agree
- Neither agree nor disagree
- Disagree
- Strongly disagree
- Very strongly disagree

Q6b. Please expand on why you hold this point of view.

Q7. Do you condition players outside of peak periods (e.g., pre-season) to be able to cope with an increased duration/load associated with extra-time.

- Yes (please specify how this is managed)
- No (please specify why (i.e., barriers to implementation))
- Sometimes (please specify)

Q8a. Do you adapt any of the recovery practices below **immediately** following a match that proceeds to extra-time, when compared with a typical 90-minute match duration?

(Select all that apply)

- Cool down (please specify)
- Nutritional intake (please specify)
- Any other specific modality (please specify)
- No changes (please specify why (i.e., barriers to implementation)

Q8b. Do you adapt any of the recovery practices below during the **24-hour period** following a match that proceeds to extra-time, when compared with a typical 90-minute match duration?

(Select all that apply)

- Cool down (please specify)
- Nutritional intake (please specify)
- Any other specific modality (please specify)
- No changes (please specify why (i.e., barriers to implementation)

Q8c. Do you adapt any of the recovery practices below during the **<u>24–48-hour period</u>** following a match that proceeds to extra-time, when compared with a typical 90-minute match duration?

(Select all that apply)

- ○ Cool down (please specify)
- ○ Nutritional intake (please specify)
- ○ Any other specific modality (please specify)
- ○ No changes (please specify why (i.e., barriers to implementation)

Q8d. Do you adapt any of the recovery practices below during the **<u>48–72-hour period</u>** following a match that proceeds to extra-time, when compared with a typical 90-minute match duration?

(Select all that apply)

- ○ Cool down (please specify)
- ○ Nutritional intake (please specify)
- ○ Any other specific modality (please specify)
- ○ No changes (please specify why (i.e., barriers to implementation)

Q9. If given the option (i.e., if money, facilities and time etc. allowed), what would you change with regards to player recovery following an extra-time match, when compared with a typical 90-minute match?

Q10. Are players monitored following an extra-time match (e.g., GPS, physiological/metabolic markers, performance tests etc.) and returned back to training based on these fatigue markers?

- Yes (please specify which monitoring tools you use)
- No (please specify why (i.e., barriers to implementation))
- Sometimes (please specify)

Q11. Can you highlight any other strategies that are used to ensure optimal player readiness following an extra-time match?

Q12. How important do you think it is to adapt training loads following extra-time matches, when compared with a typical 90-minute match?

(1 = no importance, 5 = very important)

- 1
- 2
- 3
- 4
- 5

Q13. How important do you think it is to adapt training intensities following extra-time matches, when compared with a typical 90-minute match?

(1 = no importance, 5 = very important)

- 1
- 2
- 3
- 4
- 5

Q14. Do you believe that more research should be conducted on the recovery response following the extra-time period?

- Yes
- No (please specify why)

Q15. Which of the following areas of research do you think warrant further investigation following an extra-time match?

Please rank in order of important to least important.

(1 = most important, 5 = least important)

- Tracking physical and physiological response
- Changes in acute injury-risk
- Nutritional interventions to accelerate recovery
- Non nutritional interventions to accelerate recovery (e.g., cryotherapy/ compression garments)
- Other (please specify)

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