Effects of Minor Gaelic Football Match Play on Markers of Muscle Damage, Delayed Onset Muscle Soreness and Muscle Function

Dermot Sheridan, BSc

January 2021

Effects of Minor Gaelic Football Match Play on Markers of Muscle Damage, Delayed Onset Muscle Soreness and Muscle Function

Dermot Sheridan, BSc.

Submitted for the award of MSc

Dublin City University

School of Health and Human Performance

Supervisor: Prof. Niall M. Moyna

Submitted: January 2021

Declaration

I hereby certify that this material, which I now submit for assessment of the program of study leading to the award of MSc. is entirely my own work, that I have exercised reasonable care to ensure that the work is original and, to the best of my knowledge, does not breach any law of copyright and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: _____ ID No. 14212510 Date _____

Acknowledgements

I would like to acknowledge and sincerely thank the following:

Prof. Niall Moyna for his help, guidance, and patience throughout my time in DCU. He has inspired me to strive for continual improvement and pursue the highest standard in my work and always gave me the confidence to believe in myself. His mentorship and friendship have played a significant role in shaping me personally and academically, and his impacted on my sporting career will be forever a source of pride. I had the unique experience as a player under him and as a coach with him. He has left a lasting impression upon all of my future pursuits. For all this, I am extremely grateful.

A special thanks to Kevin and Cathal, who began this journey with me all those years ago and has been a constant on my academic journey. Our friendship is one of the highlights of my time in DCU. Sinead, my brilliant cousin who started me on this journey and who is a constant source of inspiration, well done on all your continued success.

Mickey, words can't describe your effect on my life, your motivation, guidance and vigor for life has influenced me so much personally, academically and in my development as a player and to s coach, I'm so grateful for your mentorship.

Paul my close friend and without your encouragement, motivational talks I would have faltered some many times along the way. Ciaran, a young man I hold in great esteem, thank you for all the tea and good conversation and your friendship.

Clare, Nikki, Aidan, Kevin and Eoin your incredible support was very appreciated during my time in DCU, you all helped make the journey more enjoyable. Emma & Finn we shared so much and I thoroughly enjoying our experience of DCU together. The rest of my fellow postgrads and the staff in the School of Health and Human Performance, a warm thank you for their friendship and support throughout.

I am grateful to Sports Science team of Eoin, Javier and Enda for their help with the testing and analysis. To my good friend and colleague Alan that you for your expertise in transforming and engineering my data. Aisling, for all your help, which never came without a smile and a joke. I would like to thank all the subjects who took part in the study and helped out in any way.

I would like to thank my parents, family and friends for their support over the last 34 years. I know that they were always there for me when I needed them. Especially to Joe, Kathryn and Emer opening up your home to me and making me feel so welcome, thank you. I would especially like to thank my Mum & my sister Julie, for all your help and for encouraging me to return to education and take on this project. This one is special for me, Mum thank you for all the support throughout my academic life, you provided me every opportunity to pursue my dreams and this as much your as mine. Julie without your continuing support to follow my path I would be forever stuck, and I sincerely thank you.

I would also like to mention Alex for all her constant support, encouragement and love.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

±	Plus or minus
%	Percentage
Beats.min^{-1}	Beats per minute
La	Lactate
Cm	Centimeter
CK	Creatine Kinase
DOMS	Delayed Onset Muscle Soreness
EIMD	Exercise induced muscle damage
GAA	Gaelic Athletic Association
AFL	Australian Football League
DJ	Drop Jump
PP	Peak Power
PF	Peak Force
h	Hour
CMJ	Countermovement Jump
MS	Muscle Soreness
M	Mean
RPE	Rate of Perceived Exertion
BMI	Body Mass Index
$\dot{V}O_2$max	Maximal Aerobic Capacity
GPS	Global Positioning System
Sec	Second
NMF	Neuromuscular Fatigue
SD	Standard deviation
PRFD	Peak Rate of Force Development
m	Meter
m.s^{-1}	meter per second
m.s^{-2}	meter per second squared
R	Pearson product of moment correlation coefficient
Cm	Centimeter
ANOVA	Analysis of variance
Hz	Hertz

Abstract

Dermot Sheridan, BSc.

Title: Effects of Minor Gaelic football match play on markers of muscle damage, delayed onset muscle soreness and muscle function

Purpose: This study examined the alterations in circulating creatine kinase (CK) levels, leukocyte trafficking, delayed onset muscle soreness (DOMS), muscle function in response to Gaelic football match-play in male adolescents.

Methods: Participants (n=30, age 17.41 ± 0.78 yr, height 176.42 ± 7.13 cm, and mass 72.03 ± 6.49 kg) played a specially organised 15-a-side Gaelic Football game of 60 min duration. Blood samples were taken before the game, immediately post-game (Post), 12 h post-game (12 h), 36 h post game (36 h) and 60 h post game (60 h). Subjective muscle soreness, sprint performance and peak force were measured post, 12 h, 36 h and 60 h. Heart rate and movement patterns were continuously measured throughout the game using telemetry and GPS tracking, respectively. Heavy to severe impacts were classified as acceleration G-forces $\geq$ 7 recorded via portable accelerometry.

Results: Participants covered an average distance of 6.1 $\pm$ 1.1 km during match play. The majority (72%) of the distance involved walking and jogging and high speed and maximal activity accounted for 10% of the total distance. There was a total of 155 impacts $\geq$ 7 G-forces. CK levels were significantly higher than baseline immediately post-game and 12 h

and returned to pregame values at 36 h. Compared to pre-match values circulating leukocytes and granulocytes were significantly higher than pre-game values immediately after the game and decreased significantly below pre-games values at 12h, 36 h and 60 h. Circulating lymphocyte numbers were significantly decreased below immediately post game and at 36 h post game. There was no change in the number of circulating monocytes. Compared to pre-game values, there was a significant decrease in peak force at 12 h and 60 h and a significant increase in 5 m and 20 m sprint times at +12 h, +36 h and 60 h. DOMS scores were significantly higher than pre-games values at 12 h and 36 h and lower ($p<0.05$) than pre-game values at 60 h. There was no significant relation between impacts and CK levels.

Conclusion: Competitive Gaelic football match results in significant changes in CK levels, DOMS, leukocyte trafficking, peak force and 5 m and 20 m sprint performance.

CHAPTER I

INTRODUCTION

Exercise induced muscle damage (EIMD) is a condition characterized by morphological alterations of muscle tissue and is associated with a decline in muscle function [1]. It manifests as transient swelling, pain and muscle soreness and an increase in circulating levels of myocellular enzymes and proteins in the hours and days after the exercise [2–4]. A subsequent rapid and sequential invasion of muscle fibres by inflammatory cell populations and signalling molecules leads to phagocytic infiltration into the damaged muscle to clear the injured area of debris in preparation for regeneration/remodelling. It is also associated with impaired insulin stimulated glucose uptake, delayed replenishment of muscle glycogen, and a reduction in muscle function of the affected limb.

Although there is no clear consensus regarding the exact mechanism(s) responsible for EIMD, there is however, a strong body of evidence that it is linked to eccentric muscle actions involving the forcible lengthening of a contracting muscle in the presence of high force. Compared to concentric or isometric contractions, eccentric muscle actions generate greater forces for a given angular velocity [5], require less motor unit activation and use different neural control strategies [6]. The combination of high levels of force production and reduced recruitment of fiber number during eccentric contractions causes a high mechanical stress on the involved structures that may lead to greater muscle damage and negative functional consequences in an healthy naïve muscle than other types of exercise

[7]. At the cellular level, impaired excitation-contraction coupling results in a transient reduction in muscle function [8–10]. Blunt force trauma resulting from frequent, high-impact body collisions during participation in invasion team sports such as rugby league and Australian football may also contribute to muscle damage [11,12].

Histological evidence is required to directly assess muscle damage [13]. Collecting tissue samples requires multiple biopsies from the same muscle, which can be unpleasant and may also increase inflammation, independent of exercise. A number of surrogate makers are commonly used to assess EIMD. These include subjective rating of muscle soreness, changes in range of motion around a specific joint or body part, measurement of muscle function and blood levels of inflammatory markers and myocellular enzymes. None of these surrogate markers are considered to be gold standard, but each has its own advantages and disadvantages. Creatine kinase (CK), a myocellular enzymes is the most commonly used biomarker of EIMD in sport and elevated plasma levels has been reported following Australian football, soccer, rugby league and rugby union [14–16].

Gaelic football is one of the most popular sports in Ireland. It is an invasion team-based sport that can best be described as a hybrid of soccer, rugby, Australian football and basketball. Match play is characterized by repeated bouts of high-intensity short-duration activities involving accelerations, decelerations, directional changes and frequent high-impact body collisions superimposed on the technical activities. The purpose of this study

was to examine the effect of competitive Gaelic football match play on circulating CK levels, leukocyte trafficking, muscle soreness and muscle function.

Aims

1. To evaluate circulating levels of CK before, immediately after and 12, 36 and 60 h following Gaelic football match play
2. To evaluate muscles soreness before, immediately after and 12, 36 and 60 h following Gaelic football match play
3. To evaluate circulating levels of leukocytes before, immediately after and 12, 36 and 60 h following Gaelic football match play
4. To evaluate muscle function before, and 12, 36 and 60 h following Gaelic football match play

Hypothesis

1. Compared to pre-game values, circulating levels of CK will be significantly higher, immediately after and at 12 h after the Gaelic football game
2. Compared to pre-game values, DOMS will be significantly higher, immediately after and 12 h after the Gaelic football game
3. Compared to pre-game values, leukocyte trafficking will be significantly higher, immediately after and 12 h after the Gaelic football game
4. Compared to pre-game values, musc**le** function will be significantly impaired at 12 h and 36 h after the Gaelic football game

CHAPTER II

REVIEW OF LITERATURE

Skeletal Muscle Structure and Function

Skeletal muscle is a dynamic tissue comprising 50 - 75% of all body proteins. The total skeletal muscle mass is dependent on the balance between protein synthesis and degradation, with both processes sensitive to genetic and environmental factors such as exercise, nutrition, drugs and injury. [17]. The entire skeletal muscle is surrounded by the epimysium, a layer of fibrous connective tissue muscle. Groups of fibers are arranged in bundles called fasciculi that are surrounded by another layer of connective, the perimysium.

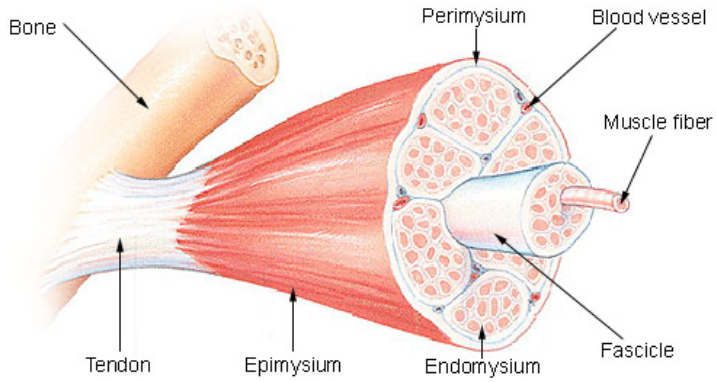

Figure 2. 1 Basic structure of skeletal muscle

Each fascicle consists of multinucleated muscle fibers surrounded by a plasma membrane, the sarcolemma. Transverse tubules (T-tubules) formed by transverse invaginations at 2 mm intervals along the sarcolemma allow action potentials on the surface of the cell to propagate deep into the cell. T-tubules contain voltage sensitive L-

type calcium channels that are composed of α_1,α_2,β,γ and δ subunits. The α_1 subunit binds to the dihydropyridine class of calcium channel blocking drugs (nimodipine and nitrendipine) and is also called the dihydropyridine receptor (DHPR). The T-tubules are flanked by the sarcoplasmic reticulum that contain Ca^{2+} release channels called ryanodine receptors (RyR1s) on their surface. Direct interaction of DHPRs and RyR1s allows for the transmission of electrical signals from the sarcolemma to the sarcoplasmic reticulum.

Each muscle fiber is comprised of thousands of myofibrils and contains billions of myofilaments that form sarcomeres, the functional units of the skeletal muscle[18]. Sarcomeres extend between two successive Z discs and contains actin and myosin protein myofilaments (Figure 2.2).

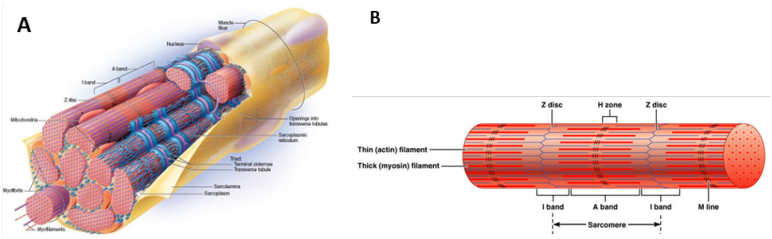

Figure 2. 2 Basic structure of a skeletal muscle fibre (A) and an individual sarcomere (B)

Actin filament are formed when multiple G actin monomers polymerize to form two fibrous (F) actin strands that are arranged in a double helix and contain a myosin binding site. The actin filaments are anchored to adjacent sarcomeres by Z discs. Myosin is a hexameric protein that interacts with the actin filament during muscle contraction [19]. In strong denaturing solutions, myosin dissociates into two heavy chains and four light chains (Figure 2.3). The two heavy myosin chains wrap around each other to form a double helical

structure. Both heavy chains are folded at one end into separate globular structures to form the two heads, each containing both regulatory and essential light chains. In addition, each globular head has a binding site for both actin and ATP.

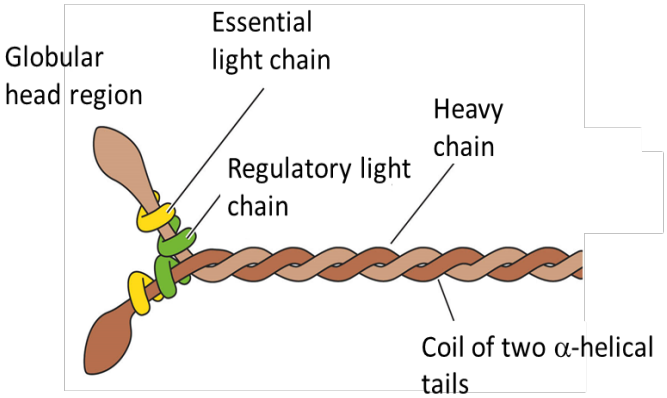

Figure 2. 3 Molecular structure of myosin filament

A number of other proteins add structural support and aid the excitation and contraction coupling process required to generate force. Tropomyosin is an actin binding protein consisting of a coiled-coil dimer that forms a polymer along the length of the actin filament. Along with the trimeric calcium-dependent troponin molecule, tropomyosin plays an important regulatory role in muscle contraction[20].

Titin is a large protein (~3.0 - 3.7 MDa) that extends from the Z-disc to the M-line, effectively binding myosin to the Z-disc (Figure 2.5). It also acts as an elastic scaffold that centres the A-band in the centre of the muscle sarcomere [21]. The degree of overlap between actin and myosin filaments determines the sarcomere's force-generating

capacity. Titin along with nebulin, an actin-binding protein (600- 900 kDa) contribute to the structural integrity of the sarcomere (Figure 2.4) and provide resistance to the stretch of the sarcomere [22]. Damage to titin following repetitive eccentric exercise is associated a loss of the normal regular arrangement of the A-bands.

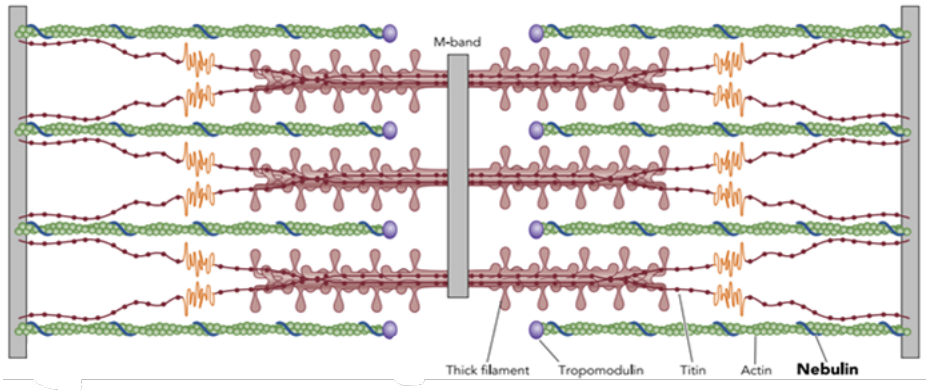

Figure 2. 4 Structural organization of the skeletal muscle sarcomere

Significant variability in the contractile, metabolic, structural and functional characteristics of individual fibers have led to adult human muscle fiber beings classified as type I (slow, oxidative, fatigue resistant), type IIA (fast, oxidative, intermediate metabolic properties), and type IIx (fast, glycolytic, fatigable). Time to peak tension is longer in slow twitch compared to fast twitch fibers due to the difference in ATPase activity on the globular head of the myosin heavy-chain head [23].

Extracellular Matrix

The extracellular matrix (ECM) is a non-cellular three-dimensional macromolecular network composed of collagens, proteoglycans, elastin, fibronectin, laminins, and several other glycoproteins (Figure 2.5). This network provides a physical scaffold for the muscle

fibre cytoskeleton cells to ebbed themselves while also regulating cellular process including growth, migration, differentiation, survival, homeostasis and morphogenesis [24]. The ECM also provides elasticity, tensile strength, compressive strength and mediates protection by a buffering action that maintains extracellular homeostasis and water retention.

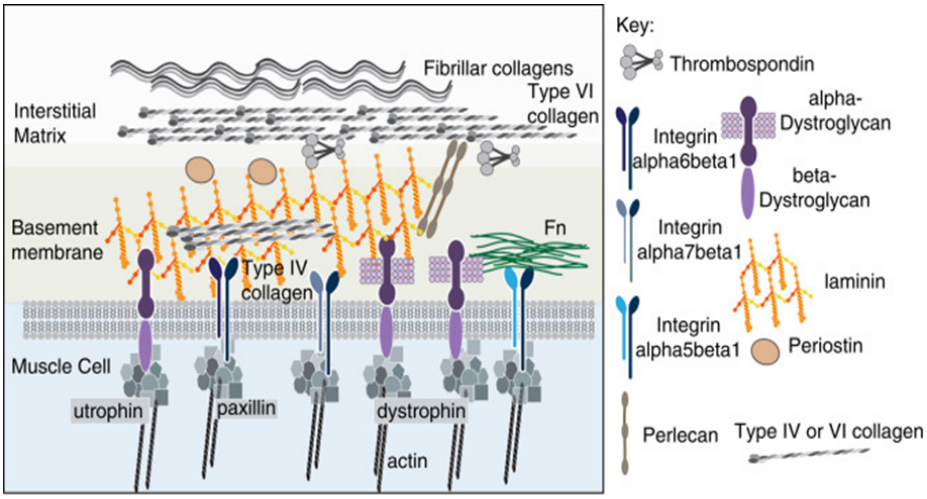

Figure 2. 5 Extracellular Matrix Network in Skeletal Muscles

Collagens are a family of over 20 different EMPs that provide structural support to tissues. They are composed of three separate collagen polypeptides organized into triple helical, coiled-coil collagen subunits. Cross-linked polymers of insoluble fibronectin homodimers assemble into fibrils in the ECM matrix and connect cells to collagenous matrices that contain fibrillar collagen. Fibronectin fibrils also exhibit salient elastic properties.

Elastin monomers provide tissues with the ability to stretch and recoil. The strength of elastin fibers arises from covalent crosslinks formed between lysine side chains

in adjacent elastin monomers. Their elasticity arises from the hydrophobic regions, which are stretched by tensile forces and spontaneously re-aggregate when the force is released. Laminins are comprised of three different subunits wrapped together in a coiled-coil configuration. By linking with proteins, laminins form complex webs in the ECM. The primary function of laminins is to provide an adhesive substrate for cells and to resist tensile forces in tissues. A network of membrane-spanning integrin, dystroglycan and proteoglycan complexes facilitates the mechanical link between the ECM scaffold [25].

Excitation- Contraction Coupling: Muscle Activation

Excitation-contraction coupling is the process whereby electrical events in the sarcolemma of a muscle fibre are linked to the actin and myosin filaments. An action potential that arrives at the sarcolemma is transmitted to the interior of the muscle cell via the T-tubular system triggers the release of Ca^{2+} from the sarcoplasmic reticulum into the sarcoplasm. Binding of Ca^{2+} to troponin C results in a conformational change in tropomyosin so that it no longer blocks the active site on the actin molecule. Exposing the active site allows the binding of myosin head with actin to form a cross bridge. The presence of both ATP and ATPase on the myosin head facilitates the detachment of the myosin head from the actin binding site and the continued formation of cross-bridges resulting in contraction [26]. This is known as the sliding filament theory and is the accepted explanation for the generation of force [27]. The phosphagen system, anaerobic glycolysis and oxidative phosphorylation are the primary metabolic pathways used to provide energy

to resynthesize ATP during exercise. Although all energy producing pathways are active during exercise, one or more pathways may be preferentially used depending on the exercise mode, duration and intensity [17].

Satellite Cells

Satellite cells are the stems cells of skeletal muscle. They are located between the sarcolemma and basal lamina and contribute to the growth, repair, and regeneration of muscle cells (Figure 2.6) [28]. Quiescent satellite cells are activated in response to external stimuli such as exercise or injury [29]. Following activation, satellite cells express myogenic regulatory factors and proliferate into the damage segments of muscle fibres where they fuse with each other to form myotubes [30].

A myogenic regulatory factor family of transcription factors including MyF5, MyoD, and MRF4 control myogenic differentiation during development and, direct satellite cells to regenerate skeletal muscle. They are also involved in satellite cell lineage specifying which members become resident stem cell [31]. One other important transcription factor in the regulation of satellites progenitor cells is Pax7. It has been shown to be upregulated in response to muscle trauma and plays a critical role in satellite propagation and self-renewal [32].

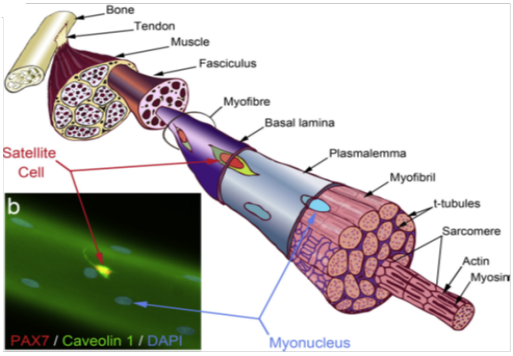

Figure 2. 6 Muscle Structure and the satellite cell niche

Exercise Induced Muscle Damage

Physical damage to the muscle structure in response to exercise commonly referred to as exercise induce muscle damage (EIMD) [33–35] is characterized by transient ultrastructural myofibrillar disruption, loss of muscle strength and power, delayed onset muscle soreness (DOMS), swelling, reduced range of motion of the affected limb, and the systemic efflux of myocellular enzymes and proteins. The initial phase of EIMD can be characterized by ultrastructural damage and Z-line streaming due in part to the heterogeneity in sarcomeres length [36]. Some sarcomeres can resist actions more than others due to different structural protein arrangements. For example, type 2 muscle fibers have thinner Z-lines than type I fibres making them more sensitive to overstretching. Disturbance in the Z-line was is greater at 24 h and 48 h post exercise compared with pre and immediately post-exercise [37].

Disruption of connective tissue in the muscle or their attachments is also commonly associated with EIMD. In particular, significant damage is found in the perimysium and

endomysial regions of the muscle where the area of the ECM is pulled away from fibers to create a widened interstitial space[37], [38]. It has been speculated that the loss in muscle force may be due to disruption to the cytoskeletal, costameric and extracellular matrix proteins following muscle damage [39,40]. Damage to the ECM following eccentric exercise may also play a role in stimulating the release of growth factors involved in satellite cell activation [41]

The extent of EIMD is affected by multiple factors including mode of muscle activation, the muscle group exercised, the volume, intensity, novelty of exercise, individual fitness and genetic variability [2]. The magnitude of the injury and the recovery process can be assessed directly or indirectly. Direct assessment requiring serial muscle biopsies can be unpleasant and unreliable and repeat biopsies from the same muscle may cause muscle damage or accentuate existing muscle damage. Furthermore, the analysis of such a small area of muscle may potentially over-or-underestimate the degree of muscle damage. Blood levels of myocellular enzymes and inflammatory markers, muscle function, subjective rating of muscle soreness are commonly used as indirect markers of muscle damage [42]. However, none of the indirect markers are considered "gold standard", but each has its own advantages and disadvantages [43,44].

Muscle-Specific Proteins

A number of muscle proteins have been used as surrogate biomarkers for EIMD including creatine kinase (CK), myoglobin, troponin and myosin heavy chain [45]. The initial

appearance of these proteins in the circulation is believed to be due the mechanical-induced damage to myofibril membranes [46] with over activation of calcium channels responsible for persistence permeability over several days [43].

Creatine kinase (CK) is the most commonly used biomarker of EIMD due to the magnitude of the response observed [43]. It is a dimeric globular protein consisting of two subunits with a molecular mass of 43 kDa. The primary functions of CK are to regulate high energy phosphate production within contractile tissue and to shuttle phosphocreatine (PCr) from the site of adenosine triphosphate (ATP) production in the mitochondria to the site of utilization in the cytoplasm (Figure 2.7).

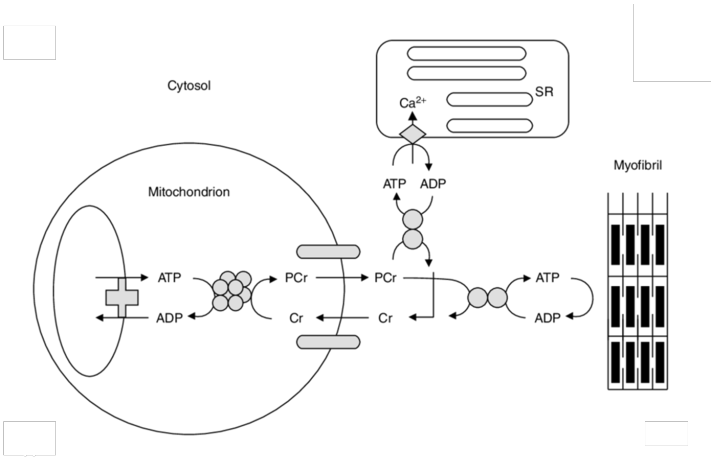

Figure 2. 7 Schematic representation of the creatine kinase (CK)-phosphocreatine (PCr) system in muscle.

Three CK isoenzymes (CK-MM, CK-MB and CK-BB) are found in the cytoplasm and the mitochondria. An active gene on chromosome 19 and chromosome 14 encodes the M (43 kDa) and B subunits (46 kDa), respectively. The subunits combine to form the various

isoenzymes. The isoenzymes are named for the tissues from which they were historically isolated; CK-MM (muscle), CK-MB (myocardium) and CK-BB (brain). CK-MB consists of a hybrid of M and B subunits and is spontaneously produced *in vitro* following the dissociation of MM and BB. Mitochondria CK catalyses the reversible transfer of a phosphate group from ATP generated by oxidative phosphorylation to a molecule of creatine to form phosphocreatine (PCr). The cytoplasmic CK isoenzymes catalyse the reverse reaction to provide a rapid source of energy for regeneration of ATP needed to support muscle metabolism during high intensity activities. Cytosolic CK consists of an M and B subunit.

The tissue distribution of CK isoenzymes is illustrated in table 2.1. Skeletal muscle consists primarily of the cytoplasmic CK-MM isoform [47]. It is found bound to the Z-line structure of the sarcomere, the M-line structure of the sarcoplasmic reticulum and in the I-band of the sarcomere [48]. CM-MB is found primarily in the heart with trace quantities also present in skeletal muscle. CK-BB is the predominant CK isoenzyme found in the brain, colon, ileum, stomach and urinary bladder.

Table 2.1. Tissue distribution (%) of cytosolic CK isoenzymes

	Isoenzymes		
	CK-MM	**CK-MB**	**CK-BB**
Skeletal muscle	99	1	0
Myocardium	77	22	1
Brain	0	0	100
Colon	3	1	90
Ileum	3	1	96
Stomach	3	2	95

Urinary bladder	2	6	92

CK Response in team-based sports

A number of studies involving field-based team sport have reported temporal changes in blood CK levels in response to both training and competitive match play. The time course of changes in CK following a senior international rugby union game between teams ranked second and sixth in the world were investigated by Cunniffe *et al.*, (2010). Blood samples were taken from 10 players on the home team at the beginning of the camp, before the game, within 15 min of the conclusion of the game, and 14 h and 38 h into a passive recovery period. Compared to pre-game values, circulating levels of CK were 255% and 125% above baseline values at 14 h and 38 h post game, respectively. Serum CK activity at 14 h and 38 h post game was significantly related to player involvement in tackles and game contact events indicating that CK leakage may have occurred due to the cumulative muscle damage arising from blunt-trauma-like effects of tackling and contacts [49].

Among Japanese college level rugby union players, peak CK measured at 24 h was also significantly related to number of tackles performed during rugby union match play [15]. Twist and Sykes, (2011) also found a significant increase CK activity 24 h following a simulated rugby league game. Peak CK values were lower than in the rugby league game than rugby union [49]. Serum CK activity at 14 h and 38 h post game was significantly related to player involvement in tackles and game contact events indicating that CK leakage may

have occurred due to the cumulative muscle damage arising from blunt-trauma-like effects of tackling and contacts Participants in the Cunniffe *et al.*, (2010) study had just completed a period of intense competition prior to the study and it is therefore possible that cumulative tissue damage explained high pre-game CK values. It is also possible that the number and severity of physical collision were lower in the simulation rugby league game compared to the competitive rugby union fixture.

Among elite rugby union players, the average change in CK level (ΔCK) during an average of 3.4 regular season games was 927 ± 204 IU with the values being significantly higher in forwards (1439 ± 677 IU) than backs (545 ± 341 IU) [51]. A significant proportion of the ΔCK in forwards was explained by the number of tackles made and being one of the first three players to a ruck or maul. In contrast, impact, was the major positive contributing factor to the ΔCK in backs. There was a significant correlation between ΔCK and both game time and time defending in both forwards and backs. The number of scrums was also related to ΔCK in forwards. In contrast, hit-ups, first three players on attack and total impacts (the sum of tackles made, hit-ups, first three on attack and first three on attack) was related to ΔCK among the backs.

The physical demands imposed on rugby players during competitive match play vary depending on playing position. Twist *et al.*, (2012) found that the total of number of contacts during a competitive game was higher in forwards than backs. However, the backs generally played longer resulting in more contacts per minute for the forwards in

comparison to the backs. Forwards were involved in a greater number of defensive tackles while both forwards and backs groups had similar numbers of offensive tackles. Among elite young professional soccer players 24 h post game CK levels were found to be associated with soccer- specific playing actions including high intensity distance, number of sprints and number of hard decelerations correlated with peak CK [53].

McLellan et al., (2010) examined the CK response to rugby league match play in 17 elite male rugby players with an average age of 19 years. Blood samples were taken at 24 h and 30 min pre-match, within 30 min of the game and 24 h, 48 h, 72 h, 96 h and 120 h post-match. Players wore a GPS receiver with an integrated triaxial accelerometer and their movement patterns were recorded as average running speed ($m \cdot s^{-1}$), average distance travelled and the distance travelled in different speed zones ranging from standing/walking (0-1.6 $m \cdot s^{-1}$) to sprinting (>5.6 $m \cdot s^{-1}$). Impacts were classified based on gravitational force (G force). Zone 1 (<5.0- 6.0 G) and zone 6 (> 10.1 G) characterized the lowest and highest impact or velocity of collisions, respectively. The average number of tackles (event that halted the progress of an opponent in possession of the ball) and hit-ups (player being tackled in possession of the ball during match play) were determined via post-match video analysis.

Match intensity was maintained and running performance did not deteriorate during the game. Backs did however travel significantly greater distances than forwards at velocities >5.0 $m \cdot s^{-1}$. Baseline CK values at 24 h pre and 30 min pre were 256 $\pm$ 113 ($U.L^{-1}$)

and 302 $\pm$ 128 ($U.L^{-1}$), respectively. With the exception of the 30 min pre-match value, all other CK values up to day 5 (120 h) were significantly higher than the 24 h pre-match value. Plasma CK peaked at 267 % (941 $\pm$ 392 $U.L^{-1}$) above the 24 h pre-match value, 24 h after the game. The fact that the study participants continued to participate in all team recovery and training sessions, may explain the elevated CK values 5 days after the game. There was no relation between CK levels and distance travelled during the game. In contrast, the number of impacts >7.1 G was significantly related to the extent of muscle damage as measured by plasma CK levels at 30 min and 24 h post-match. There was also a significant relation between the number of impacts > 8.1 G and plasma CK levels at 48 h and 72 h post-match indicating that very heavy impacts are associated with an increase in CK for a least 5 d. The combined total number of hit-ups and tackles was significantly related to plasma CK levels at 30 min, 24 h, 48 h and 72 h post-match. When analyzed separately only the number of hit-ups was related to CK levels at 24 h, 48 h and 72 h post-match. The data indicate that repeated high intensity collisions during elite rugby league match play is associated with significant skeletal muscle damage for up to 72 h. Using a cross-over, counter-balanced study design Johnston *et al.*, (2014) found that the addition of physical contact to small sided 6 v 6 rugby league game also resulted in marked and longer lasting increases in CK compared to no physical contact.

The effect of a single competitive game of elite soccer on circulating CK markers was monitored over a 6 d recovery period [55]. Peak CK value of 950 U/L occurred at 48 h

post game and persisted for up to 72 h. A similar finding was reported in sub-elite U-21 soccer players following participation in a competitive game [56]. Study participants abstained from strenuous physical activity 7 d prior to the game. Blood levels of CK peaked at times the baseline value 48 h into recovery and remained elevated throughout the 7 d recovery period. Pre-match CK levels were found to be 485% greater than baseline levels among Australian football players suggesting that the recovery time between games may be inadequate. More recently, Djaoui *et al.*, (2016) reported a 475% increase in CK (228 ± 185 vs, 1141 ± 1365 U/L) among a group of professoinal soccer players 24 h after a competitive fixture. CK levels remain elevated, but not significantly (729 ± 1124 U/L) at 48 h.

Among reserve team players from an English Premier League club, CK levels were found to elevated above pre-game values at 48 h after each of 4 competitive games played over a 3 month period post game [58]**.** The responses were consistent across the different matches and playing positions. Professional soccer players participating in daily training have been reported to demonstrate persistent high-resting CK values [59]

Australian football is very similar to Gaelic football. Young, Robbins and Hepner, (2012) split 14 elite junior ARF players (aged 16–18 years) based on CK levels following a single game into a high and low CK group. Distance covered during running between 4 and 7 $m \cdot s^{-1}$, moderate acceleration, and moderate to high deceleration were variables best able to distinguish between players who produced relatively high CK from those who produced

lower CK levels. These findings suggest that among elite junior Australian football players certain levels of volume for specific movement variables are necessary to influence CK levels.

Hunkin, Fahrner and Gastin, (2014) measured pre-match CK levels in 29 elite Australian Rules Football AFL players across ten rounds of the Australian Football League (AFL). The average pre-match [CK] across the season of 376 ± 161 UL was 485% greater than individual player baseline value of 78 ± 52 UL. There was considerable variability in average pre-match [CK] across the season for each player with values ranging from 145–849 U L−1).

It is not uncommon for team sports players to play multiple times per week or during tournaments. Johnston, Gabbett and Jenkins, (2012) examined the selected match performance characteristics physiological responses and perceptions of fatigue to an intensified period of rugby league competition in 15 junior rugby league players (7 backs, 8 forwards). Participants played five separate 40 min games over a 5 d period. Two games were played on day 1 and day 2 and one game on day 4. No games were played on day 3 or day 5. Blood samples were taken and neuromuscular fatigue was assessed 1 h before and within 1 h post-game and 12 h and 24 h post-game 4 and game 5, respectively. CK peaked 1 h after game 4 and remained elevated above baseline values on day 5 in both positional groups. The peak CK values ranged much lower than the values reported for regular 13-a-side rugby league games. The mean CK values of the forward players was

significantly higher than baseline at all time-points over the 4 days. CK values were only significantly elevated in backs at 1 h post-games 2 and 4 and 1 h pre-game 3. Forwards had a greater number and frequency of collision than backs and there was a significant relation between the frequency of collisions and increases in CK over the 5 d period. Cumulative fatigue appeared to compromise the volume of high-intensity running, maximal accelerations and tackling ability during the latter part of the tournament. Interestingly, overall perceptions of well-being decreased over the five days due primarily to perceptions of muscle soreness and fatigue.

Coutts *et al.*, (2007) monitored CK in 18 semi-professional rugby league players who were randomly assigned to 6 weeks of normal training or intensified training (deliberate over-reaching). Blood samples were taken 24 h prior to the training program and following 2, 4 and 6 weeks of training. CK activity was significantly increased for both groups at week 6. The levels of circulating CK were 214% and 99% in the normal and intensified training groups, respectively at week 6.

Kraemer *et al.*, (2013) investigated the changes in CK across a season in 22 Division 1 collegiate level American Football players. Baseline values were obtained before the start of preseason practice with subsequent data recorded 2 weeks later, the day after game 2, game 4, game 6 and game 9 of a 12-game season. While no significant elevations of CK were found throughout the season, CK was found to be at the highest value (495.1

$U \cdot l^{-1}$) after game 9. It is possible that optimal strength and conditioning and sports medicine programs may have contributed to the findings.

Limitations to the use of CK

The use of circulating muscle proteins as a marker of EIMD is problematic because blood levels at any time reflects the balance between their release from the muscle and clearance from the blood. Due to its size, CK is taken up by the lymphatic system and subsequently enters the bloodstream via the thoracic duct (Sayers & Clarkson, 2003). The slower lymphatic flow compared to the general circulation delays the appearance of CK in the bloodstream. There is also large interindividual variability in the CK response following EIMD. [64]. A polymorphism in the myosin light chain kinase (MLCK) gene has been shown to associated with small but significant differences in post-exercise CK levels [65]. EIMD and accompanying increase in circulating CK levels in response to eccentric muscle actions is further accentuated by repeated blunt force trauma related collisions in invasion team-based sports such as rugby, Australian football, and American football.

Repeat bout effect

Strength loss, DOMS and circulating muscle proteins are attenuated in response to eccentric exercise performed within 6-months of the original stimulus. This has led to the term "repeat bout effect" being introduced by Nosaka and Clarkson in 1995 [66]. A potential explanation may be the that adaptations in response to the first bout of exercise may make the muscle less susceptible to damage by subsequent exercise bouts [67]. For example, weak

muscle fibers that are physically damaged are replaced by stronger fibers that are less susceptible to injury. In addition, physical restructuring of the muscle would include sarcomere addition to existing fibers [68] and remodeling of the intermediate filaments [69]. The de-adhesion of the EMC from the muscle fiber and subsequent repair following the initial bout may also protect the muscle against subsequent injury during a second bout [70].

Delayed Onset Muscle Soreness

Delayed-onset muscle soreness (DOMS) refers to unpleasant, dull, aching pain, usually felt during palpation, contraction or stretching of the activated musculature 24 - 48 h following unaccustomed exercise with an eccentric component or in response to the repeated trauma associated with many invasion team sports [43]. The muscle soreness progressively subsides and disappears within 5–7 d [71]. The pain and discomfort associated with DOMS can however, discourage exercise participation and decrease exercise performance.

Although, muscle soreness is a well-recognised marker for muscle damage in athletic populations [72], it shares a poor temporal relation with histological evidence of muscle damage. Impairment in muscle function following intense exercise normally occurs prior to the appearance of muscle soreness and EIMD may continue to worsen, even after soreness has dissipated [73].

The mechanisms responsible for the DOMS are not fully understood. There is accumulating evidence that invading inflammatory cells may play a role after eccentric exercise (Tidball and Villalta, 2010, Hyldahl *et al.*, 2011). Bradykinin, a physiologically and pharmacologically active paracrine hormone produced at the site of tissue damage is a well characterized pro-inflammatory agent. It directly stimulates sensory nerve endings, activates pain pathways and promotes neurogenic inflammation through the peripheral release of proinflammatory tachykinins such as substance P, neurokinin A and calcitonin gene-related peptide [76,77]. In addition, nerve growth factor (NGF) has been confirmed to intensify soreness after eccentric exercise in humans [78]. Swelling within the muscle at 48 h post-exercise increases intramuscular pressure [79] and may play a role in the development DOMS.

DOMS detected by palpation of the muscle was significantly increased immediately following an elite soccer and peaked at 48 h returning to baseline at 96 h post-game [55]. Interestingly, peak DOMS occurred at the same time as peak CK values. Using a visual analogy scale in sub-elite U-21 soccer Fatouros *et al.*, (2010) found that DOMS increased significantly immediately post-game, peaked at 24 h and remained elevated for 48 h. Perceived muscle soreness was also found to be significantly increased for up to 48 h following a simulated rugby league match [50]**.** More recently, a study involving elite adolescent soccer players found a significant increase in muscle soreness at 24 h but not at 48 h following a competitive game [57]**.**

Inflammation

The immune system monitors the body for the presence of foreign pathogens and recruit's immune cells to sites of infection and inflammation. Innate immunity provides a first line of defense against infection. It is composed of anatomic and physiologic barriers (skin), specialised cells (natural killer cells, neutrophils, monocytes), and soluble factors including the complement system and acute phase proteins. Acquired immunity involves an antigen-antibody response and is mediated by both B and T lymphocytes in corporation with the innate immune system. [80]. The immune response to exercise is influenced by a number of factors including age, fitness level, exercise modality and exercise intensity, volume and duration. Periods of excessive and prolonged training and competition may transiently suppress immune function increasing susceptibility to opportunistic infections (Mackinnon, 2000, Nieman, 1997).

Repair and remodeling of muscle tissue in response to muscle damage is facilitated by extensive crosstalk between skeletal muscle tissue and multiple levels of host immunity. A well-orchestrated inflammatory response assists with the removal of cellular debris and is an indispensable prerequisite for subsequent structural remodeling and functional adaptation of skeletal muscle tissue in response to EIMD (Tidball, 2005; Bessa, 2013, Tidball and Villalta, 2010). The inflammatory response involves leukocyte infiltration and the production of pro-inflammatory cytokines within damaged muscle tissue [83]. In addition, satellite cells proliferate and differentiate to repair existing muscle fibers or form new

fibers. In the absence of sufficient recovery, the damaged tissue may have insufficient time to repair, and a chronic inflammatory condition connected with overreaching may occur (Smith, 2000).

In response to EIMD, resident macrophages express several neutrophil chemoattractants including CXC-chemokine ligand1 (CXCL1) and the CC-chemokine ligand-2 (CCL2) [84]. Neutrophils also enter injured muscle tissue in response to high levels of the pro-inflammatory cytokines, interferon-γ (INFγ) and tumor necrosis factor alpha(TNF-α) [85,86]. Neutrophils and macrophages contribute the majority of the TNFα in muscle following injury [87] and loss of TNF-α signaling impairs a muscle specific gene pathway necessary for transition from proliferation to early differentiation of stages in muscle regeneration [88].

Neutrophil accumulation activates resident macrophages and attracts further macrophage invasion. Macrophages are not only phagocytic but may also promote repair and regeneration via the release of cytokines [89]. Both M_I and M_2 macrophage populations are involved with muscle regeneration [75]. The predominantly glycolytic M_1 phenotype reaches peak numbers 1-2 d post-injury and coincides with the activation and proliferation of satellite cells during early regeneration. A population of M_2 non-phagocytic macrophages possessing an oxidative phenotype replace the M_1 macrophages and peak 4 to 7 d post injury coinciding with the expression of genes that mark terminal differentiation [90]. The anti-inflammatory cytokine, interleukin-10 (IL-10) promotes the transition of

macrophages from M_1 to the M_2. IL-10 also increases AMPK activity which drives the production of anti-inflammatory cytokines and is involved in signaling the change from the proliferative to the differentiation and growth stage of myogenesis (Villalta *et al.*, 2011, Mantovani *et al.*, 2004, O'Neill and Hardie, 2013)

Muscle regeneration is regulated by a family of muscle specific transcription factors including MyoD, moygenin, Myf4, and Myf5 [94]. The initial stage involves activation of quiescent satellites cells and leads to their proliferation and expression of MyoD and Myf5 transcription factors [95]. Upon activation, satellite cells enter a cycle and divide, and either return to a quiescence state to renew the population or begin terminal differentiation to from muscle fibers. Quiescent satellites cells express Pax7 but not MyoD. Following activation, they cells express both Pax7 and MyoD and exit the cell cycle. Pax7 expression ceases in satellites cells that continue to differentiate into muscle myocytes [94,95]. Exit of satellite cells from the cell cycle coincides with the expression of myogenin and Myf4. These transcription factors along with myocyte binding factor 2 (MEF2) drive the expression of muscle specific genes that are necessary for muscle cell fusion and transition to terminal differentiation [96].

Muscle performance

Muscle force production involves a sequence of events, extending from cortical excitation to motor unit activation to excitation–contraction coupling, and ultimately leading to muscle activation [97]. A decrease in maximal force or power production in

response to EIMD is a commonly experienced phenomenon and can limit athletic performance [98]. Force loss ranging from 10%-65% of pre-exercising values have been reported [99,100]. Decrements in force output following EIMD often involves impairment or failure of excitation-contraction coupling and/or cross bridge cycling in the presence of neural signaling and may be related to inflammation and oxidative stress targeting proteins involved in muscle contraction and force production [1,101].

The reduction in force-generating capacity of the muscle is a commonly used indirect marker of EIMD [72]. A number of jump performance indices including peak muscle force, rate of force development, jump height, and flight-time characteristics are commonly used to measure lower limb muscle power [102]. Although laboratory-based force platforms provide a high degree of precision and accuracy for measuring jump performance indices, they tend to be more expensive and less feasible for the large numbers involved in team-based sports. In recent years the introduction of jump mats, photocell mats and smartphone apps have become very popular among sport teams due primarily to their ease of use, portability and low cost compared to laboratory-based force plates and motion capture systems. Jump mats consist of electric circuits that are mechanically activated by pressure [103] whereas, photocell mats consist of electric circuits that are mechanically activated by pressure [104]. Smartphone apps use high speed video recordings to compute flight time by counting the number of frames between take-off and landing [105].

The decline in force production following eccentric exercise may be due to physical damage and disruption to the sarcomeres. Non-uniform stretching occurs in sarcomeres when a muscle lengthens under a high degree of force. Weak sarcomeres may overstretch and pop resulting in a reducing in force output due to impaired excitation-contraction coupling [106]. Warren, *et al.*, (2002) proposed that the strength decrements immediately following eccentric exercise were due primarily to EC uncoupling and that strength loss beyond 3 d could be accounted for by loss of contractile protein. Force loss following eccentric exercise in mice can be restored when the EC-coupling pathways is bypassed using caffeine-induced contraction to directly open sarcoplasmic reticulum calcium channels [108]. There is large interindividual variability in force loss following eccentric exercise [109]. The α-actinin 3 (ACTN3) gene has been link to force loss after eccentric actions in humans suggesting that ACTN3 is one of many genes contributing to genetic variation in response to exercise [65].

Among elite young male rugby players, peak rate of force development and peak power were significantly decreased following a competitive game and did not return to pre-match values for 48 h [110]**.** Peak force development was also decreased after the game and did not return to pre-match values for 24 h. Interestingly, there was a significant inverse relation between the increase in CK and the decrease the peak rate of force development at 30 min and 24 h post-match. Similarly, Andersson *et al.*, (2008) found a reduction in CMJ height in the presence of a significant rise in blood CK levels after a soccer

game whereas Horita *et al.*, (1999) found a significant relation between an increase in plasma [CK] and decreased drop jump performance for 2 d after exhaustive eccentric exercise. Johnston *et al.*, (2013) evaluated the changes in peak power in junior rugby league players over a 5 d period that involved five separate 40 min games. Participants played two games on day 1 and day 2 and one game on day 4. Peak power decreased below pre-game 1 at the end of game 3 and remained significantly decreased until after game 5. Ispirlidis *et al.*, (2008). found that among 24 elite soccer players, vertical jump performance was significantly lower 24 h post-game than pre-game. CK levels returned to pre-game values at 72 h. In contrast, sprint speed declined post-game, reached its lowest value 48 h post-game, and returned to pre-game levels after 120 h. In contrast, Thorlund, Aagaard and Madsen, (2009) found no significant change in PF, PP, or rate of force development (RFD) immediately after a soccer match play. Similarly**,** [14]found no significant change in mean force and mean power immediately after a game of elite Australian Football and suggested that the CMJ may lack the sensitivity to detect neuromuscular fatigue from a single game.

By impairing muscle force generation, EIMD can have a detrimental impact on acceleration, deceleration and maximal linear sprint time. Twist and Eston, (2005) examined the effects of EMD on maximal intensity intermittent sprint performance, a pattern of activity that is common in soccer, Australian football and rugby game. The presence of muscle damage was confirmed through elevations in CK and muscle soreness.

The ability to generate peak power output (PPO) from a standing start over 10 m was reduced and sprint running time over 10 m was reduced by approximately 3%. In a follow up study, sprint times were 6% slower over 5 m and 5% slower over 10 m at 24 h and 48 h, respectively. [115]. Ispirlidis *et al.*, (2008) found a decrease in sprint speed following a soccer game. The largest decrease was at 48 h post-game, and sprint performance returned to pre-game levels after 120 h. Similarly, Fatouros et al., (2010) found a significant decline in 20 m spint performance for up to 48 h following a soccer game. In contrast, Semark *et al.*, (1999) found not effect of EIMD on single sprint efforts of 5, 10, 20 and 30 m from a standing start.

CHAPTER III

METHODS

Participants

Minor level (u-18), male Gaelic Football players with a mean (SD) age of 17.41 ± 0.78 years, BMI 22.50 ± 4.20 $kg \cdot m^{-2}$, and $\dot{V}O_2$ max 57.97 ± 6.49 kg $mL \cdot kg^{-1} \cdot min^{-1}$ (measured by open circuit spirometer) from two separate GAA clubs volunteered to participate in the study. Each player had a minimum of 5 years playing experience. The teams trained on average 2 d per week and played at least one game per week during the competitive season. Written informed consent and assent were obtained from the parents/guardians and children, respectively. The study was approved by the Research Ethics Committee at Dublin City University.

Study overview

A single group repeated-measures pre-post-match design was used in this study. Participants played a single competitive Gaelic football game. Blood samples were taken and subjective muscle soreness, sprint performance and muscle power were measured before the game (Pre), 12 h post-game (12 h), 36 h after the game (36 h) and 60 h after the game (60 h). In addition, a blood sample was also taken immediately post-game (Post). Heart rate and movement patterns were continuously measured throughout the game using telemetry and GPS tracking, respectively. The testing protocol is outlined in figure 3.1. Body composition and aerobic fitness were measured prior to the study. With the

exception of post-game blood draws, all other measurements were taken in the Human Performance Laboratory at Dublin City University. Participants were requested to refrain from strenuous physical activity during the 24 h period before the game and for 60 h after the game.

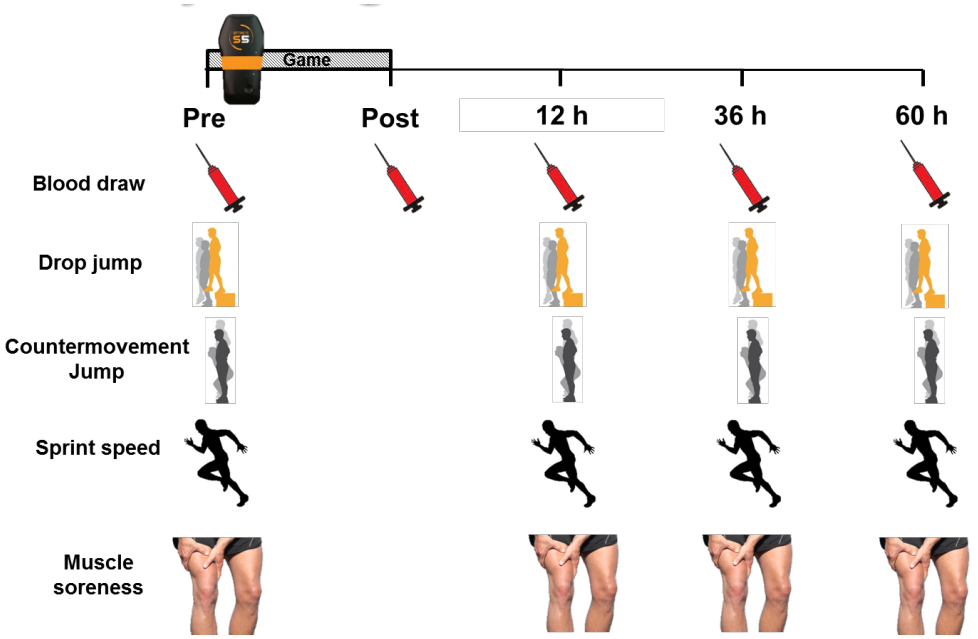

Figure 3. 1 Study design

Blood sampling and processing

Approximately 6.0 mL of venous blood was drawn at each time point from a forearm vein using standard venepuncture. Whole blood samples were centrifuged (Beckman Coulter, UK) at 3000 rpm for 15 min at 4°C. Plasma was transferred to micro centrifuge tubes and stored at -80°C for subsequent analysis. Routine complete blood counts (CBC) were performed prior to centrifugation on whole blood collected in EDTA vacutainers using an automated cell counter (Coulter Ac.Tdiff2, Beckman Coulter). Plasma

CK was measured using a Randox Datona™ clinical chemistry analyser using a CK-NAC assay. The enzyme used for the CK assay was hexokinase and the substrate was creatine phosphate $2Na4H_2O$. The absorbance level for the reaction was 340 nm. .

Height and body mass

Height and body mass were measured to the nearest 0.1 cm using a portable scale (Seca 707 Balance Scales, GmbH, Hamburg, Germany). Participants removed their shoes and stood with their feet together on the base plate with their arms loosely by their side. Body mass was measured to the nearest 0.1 kg. Participants were instructed to wear a light top and shorts, and to remove their shoes prior to the measurement

Counter movement jump

The CMJ was performed on a force plate (ONSPOT 200-1, Innervations, Muncine, IN, USA), with a sampling rate of 1,000 Hz. Participants were instructed to keep their hand on their hips, flex their lower limbs and then immediately rebound in a maximal vertical jump with no pause between the eccentric and concentric phase, and to land with both feet in contact with the force plate. No instruction was provided in terms of speed or depth of the countermovement. Three trials each separated by a 60 s rest were performed and the best score was recorded and used for analysis. Prior to performing the CMJ test, the participants completed a warm-up session consisting of 5 min of self-paced dynamic movements followed by 5 min of prescribed dynamic stretching. One practice jump was provided to familiarise participants with the test procedure.

The analog signal was converted to a digital signal using a PowerLab 30 series data acquisition system (AD Instruments, Sydney, Australia). Peak force (PF) was calculated as the maximum force achieved over the force-time curve during the CMJ. The vertical velocity was calculated from the integration of the force-time trace and was used in the calculation of peak power (PP). The vertical force was multiplied by the velocity throughout the propulsive phase of the CMJ to determine PF.

Sprint speed

A 10 min warm up including jogging, striding and dynamic movement patterns was completed prior to the sprint test. Wireless electronic timing gates (Fusion Sport International) were positioned on the starting line and at a distance 5 m and 20 m from the start line. Participants placed their front foot on a marked line, 50 cm behind the first timing gate. They were instructed to sprint as fast as possible from a stationary start through the last gate. Three trials were performed and the 5 m and 20 m times were recorded to the nearest millisecond (ms). Each trial was separated by a 3 min recovery period. Following each sprint, the time attained was provided to the participant for motivational purposes.

Movement patterns and gravitational forces

A 10-Hz global positioning system (GPS) (SPI-Pro, GPSports, Canberra, ACT, Australia) with integrated triaxial accelerometery was used to measure including total distance travelled along with specific movement patterns during match play. Six different

speed zones were classified (Table 3.1) and the frequency and duration of each entry recorded.

Table 3. 1 Speed zone classifications

Movement	Zone	$m \cdot sec^{-1}$	$km \cdot h^{-1}$
Standing	1	<0.19	<0.7
Walking	2	0.19 – 2.0	0.7-7.2
Jogging	3	2.0 – 4.0	7.2-14.0
Running	4	4.0 – 5.5	14.0-20.0
High speed running	5	5.5 – 7.0	20.0-25.0
Maximal speed running	6	> 7.0	> 25

Impacts

The intensity, number, and distribution of gravitational forces (G) experienced by participants during collisions were recorded and classified based on methods presented previously for rugby league (4) and rugby union (10) and the manufacturer guidelines (GPSports, Newry, N. Ireland). Each impact was coded to 1 of 6 zones based on acceleration G-force characteristics recorded via portable accelerometery. The impact zone characteristics are listed in Table 3.2.

Table 3. 2. Impact zones

Zones	G forces	Description
1	5.0–6.0	Very light impact, hard acceleration/deceleration/change of direction while running.
2	6.1–6.5	Light to moderate impact, minor collision with opposition player, contact with the ground.
3	6.5–7.0	Moderate to heavy impact, making tackle or being tackled at moderate velocity
4	7.1–8.0	Heavy-impact, high-intensity collision with opposition player(s), making direct front on tackle on opponent traveling at moderate velocity, being tackled by multiple opposition players when running at sub maximum velocity.
5	8.1–10.0	Very heavy impact, high-intensity collision with opposition player(s), making direct front on tackle on opponent traveling at high velocity, being tackled by multiple opposition players when running at near maximum velocity.
6	10.1	Severe impact, high-intensity collision with opposition player(s), making direct front on tackle on opponent traveling at high velocity, being tackled by multiple opposition players when running at maximum velocity.

GPS typically uses a network of satellites in orbit around the Earth. Each satellite is equipped with an atomic clock that emits, at the speed of light, the exact time and position of the satellite. The GPS receiver compares the time emitted by each satellite signal with the lag time, measured by each receiver, translated into distance by trigonometry. By calculating the distance to at least 4 satellites, the exact position and altitude of the receiver on the Earth's surface can be determined. Speed of displacement is determined via the Doppler shift method, by measuring the rate of change of the satellites' signal frequency attributable to movement of the receiver [117]. The integrated accelerometer within the GPS unit measures accelerations and decelerations (m/s^2) for each plane, with known gravity of 9.8 m/s^2 equal to 1 G. The integrated accelerometer measures the rate of acceleration and deceleration on each plane and divides the value by 9.8 m/s^2, to

determine the combined G-force as the sum of the G-force measured on each directional axis. The accuracy and reliability of the SPI-Pro have been reported previously [118,119]

Approximately 30 min prior to start the game, the GPS device, which weighed 76 g was fitted in the upper thoracic region and a heart rate telemetry unit (Polar Team Pro, Polar Precision Performance SW 3.0, Kempele, Finland) was placed around the chest. The GPS device was supported in a purpose designed harness worn underneath the playing kit. None of the participants complained of discomfort or impediment to their normal range of movement or performance from wearing the GPS equipment during match play.

The playing number of each participant and unit number of each device were recorded for identification purposes. The GPS system was synced with an electronic mobile device (iPhone 4S, Apple Inc. San Francisco, USA) that was used to manually record the exact start and end time of each playing half. The exact times of all tactical or injury enforced substitutions of monitored players were also manually recorded. Data were later downloaded from each GPS unit to a personal laptop computer where further analysis was carried out using specifically designed computer software analysis programme.

Heart rate

Heart rate was continuously measured with a sampling frequency of 5 sec using a wireless telemetry system (Polar Team Pro, Polar Precision Performance SW 3.0, Kempele, Finland). Heart rate data was stored on a receiver attached to an elastic strap placed

around the participant's chest. The data was transferred to a personal laptop computer for analysis. Individual peak HR's were identified in order to categorise HR data obtained during match play in to one of four zones: 0-60%, 61-70%, 71-80%, 81-90% and 91-100% maximal heart rate (HRmax). Similar zones have previously been used to evaluate the heart rate response in elite youth soccer players [120].

Muscle Soreness

Subjective rating of muscle soreness was measured using the pain visual analogue scale (VAS) (Figure 3.2). The VAS scale ranged from 0-100 and was anchored to written cues from left (no pain) to right (worst pain imaginable). Participants indicated their current level of pain on the Pain VAS scale line after performing a squat to a knee angle of approximately 90° with hands on hips and feet shoulder width apart and then returning to the standing position.

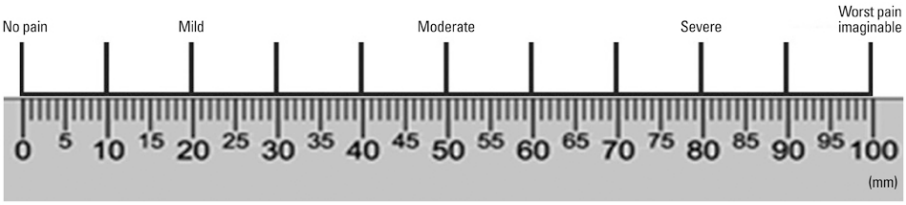

Figure 3. 2 Muscle soreness visual analogue scale

Maximal Aerobic Capacity ($\dot{V}O_2$max)

Maximal aerobic capacity ($\dot{V}O_2$max) was determined on a treadmill (Woodway ELG 55, Waukesha, WI) using a ramp protocol. The treadmill velocity was set at 10 km·h^{-1} and the gradient at 4%. Treadmill velocity remained constant and the gradient was increased

by 1% every min until volitionalefatigue. $\dot{V}O_2$max was determined by averaging the two highest consecutive 30 sec values. Heart rate, ratings of perceived exertion (RPE), expired O_2, CO_2, and ventilatory volume were continuously recorded. RPE was obtained using the 16-point Borg category RPE scale. Heart rate was measured using telemetry (Polar Vantage NV™ Polar, Port Washington, NY).

Open Circuit Spirometry

Respiratory metabolic responses were determined using standard open-circuit spirometry techniques (Sensormedics Vmax 229, SensorMedics Corp., CA). Prior to testing, the gas analysers were calibrated with standard gases of known concentration. The calibration gas was sampled at a rate of 125 Hz. A mass flow sensor (Sensormedics, Loma Linda, CA, USA) was used to collect breath-by-breath measurement of ventilation. A 3 L volume syringe (Sensormedics, Loma Linda, CA, USA) was used to calibrate the mass flow sensor prior to each test.

Statistical Analysis

Goalkeepers were excluded from the analysis. Prior to statistical analysis the data was checked for normality using the Shapiro-Wilks test. A one-way repeated measures ANOVA was used to compare the mean differences across time. Significant main effects were probed using a Bonferroni post hoc test. SPSS for Windows statistical software (ver 25.0) was used to perform the statistical analysis. The criterion for significance (alpha) was set at 0.05.

CHAPTER IV

RESULTS

Activity characteristics

The activity characteristics during match play are summarized in Figure 4.1. Players covered a total distance of 6132 ± 1090 m at a relative velocity of 100 m·min^{-1}. The majority of the total distance (72%) was covered at a velocity < 4.0 m·sec^{-1} and only 10% of involved combined high speed and maximal speed running. The maximal velocity achieved during match play was 8.16 ± 0.38 m·sec^{-1}. There was a significant difference ($p<0.001$) in the distance covered in each activity.

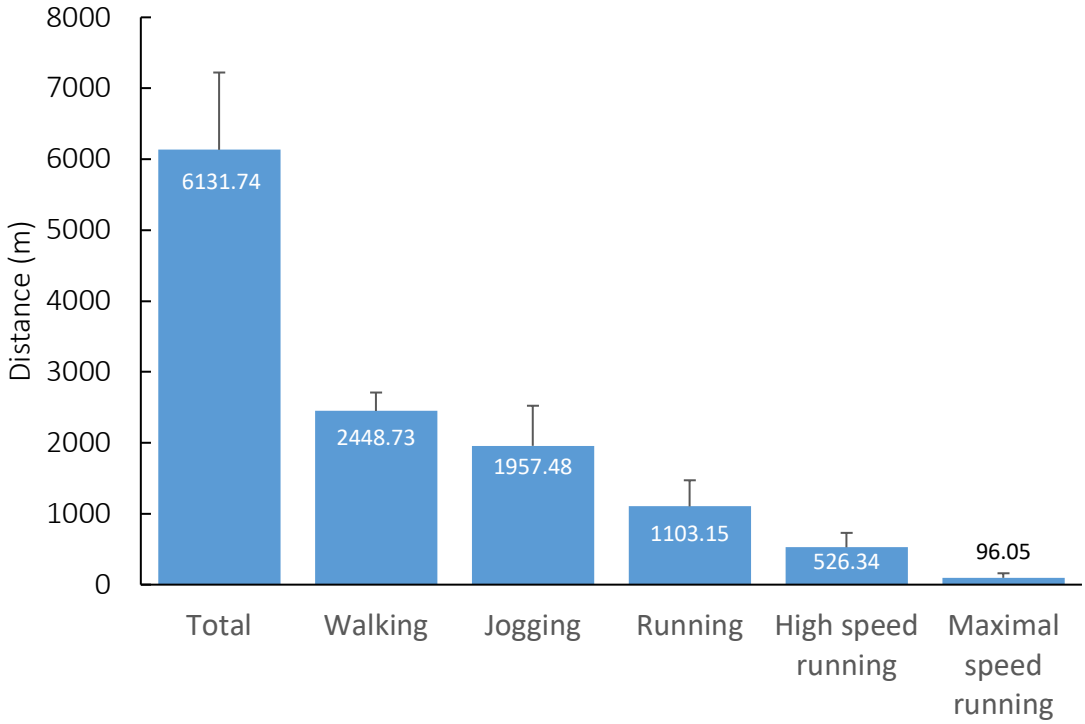

Figure 4. 1 Activity characteristics during Gaelic football match play

Creatine kinase

Figure 4.2 illustrates the average CK values. Compared to pre-game, circulating CK levels were significantly higher immediately post game ($p<0.001$) and 12 h post-game ($p<0.01$). CK levels were not significantly different from pre-game at 36 h and 60 h. There was no significant relation between impact and CK levels.

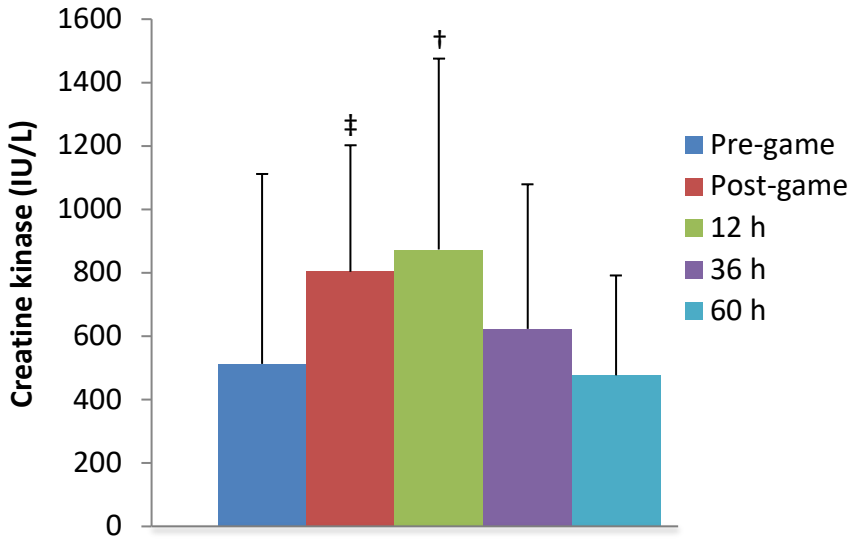

Figure 4. 2 Serum levels of CK pre-game and at 12 h, 36h and 60 h.

Values are mean ± SD, †$p<0.01$ vs. pre-game; ‡$p<0.001$ vs. pre-game

Muscle soreness

Compared to pre-game values, muscle soreness was significantly higher at 12 h ($p<0.001$) and 36 h ($p<0.01$) post game and significantly lower at 60 h ($p<0.05$).

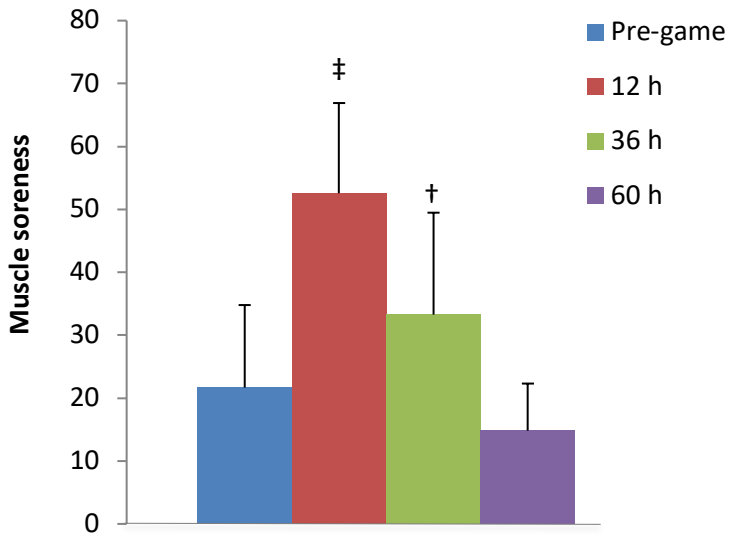

Figure 4. 3 Muscle soreness pre-game and at 12 h, 36 h and 60 h.

Values are mean ± SD, *p<0.05 vs. pre-game; †p<0.01 vs. pre; ‡p<0.001 vs. pre-game

Impact zones entries

The average number of impact zone entries are summarized in table 4.1. There were 155 (5%) impacts ≥ 7 G-forces.

Table 4. 1 Average number of impact zone entries during Gaelic football match play

1 (<5.0-6.0 G)	2508.83 ± 728.01
2 (6.1-6.5 G)	100.37 ± 42.99
3 (6.5-7.0 G)	67.10 ± 3.31
4 (7.1-8.0 G)	78.07 ± 36.32
5 (8.1-10.0 G)	55.47 ± 33.57
6 <10 G.	22.53 ± 17.27

Values are mean ± SD

Leukocyte trafficking

Table 4.2 summarizes the mean number of circulating leukocytes, granulocytes, lymphocytes and monocytes. The number of leukocyte and granulocytes was significantly higher ($p<0.001$) and the number of lymphocyte significantly lower ($p<0.001$) immediately post game compared to pre-game. Compared to pre-game values, the number of circulating leukocytes and granulocytes was significantly decreased at 12 h ($p<0.001$), 36 h ($p<0.001$) and 60 h ($p<0.001$) post-game. Circulating lymphocyte numbers were significantly lower than pre-game levels 36 h after the game. Compared to pre-game values, there was no change in the number of circulating monocytes at any time point after the game.

Table 4. 2 Absolute number of circulating leukocytes before and after Gaelic football match play

	Leukocytes	**Granulocytes**	**Lymphocytes**	**Monocytes**
Pre-game	8.59 ± 1.94	5.84 ± 1.62	2.50 ± 0.71	0.35 ± 0.20
Post-game	11.38 ± 2.20‡	8.76 ± 2.05‡	2.06 ± 0.66‡	0.33 ± 0.18
12 h	7.22 ± 1.45‡	4.56 ± 1.21‡	2.38 ± 0.73	0.34 ± 0.17
36 h+	6.84 ± 1.46‡	4.26 ± 1.31‡	2.23 ± 0.71†	0.47 ± 0.69
60 h+	6.78 ± 1.44‡	4.14 ± 1.35‡	2.36 ± 0.71	0.26 ± 0.15

Values are mean ± SD, *p<0.05 vs. pre; †p<0.01 vs. pre; ‡p<0.001 vs. pre

Muscle function

Figure 4.4 illustrates the average peak force values before and after Gaelic football match play. Compared to pre-game values, there was a significant decrease in peak force at 12 h and 60 h.

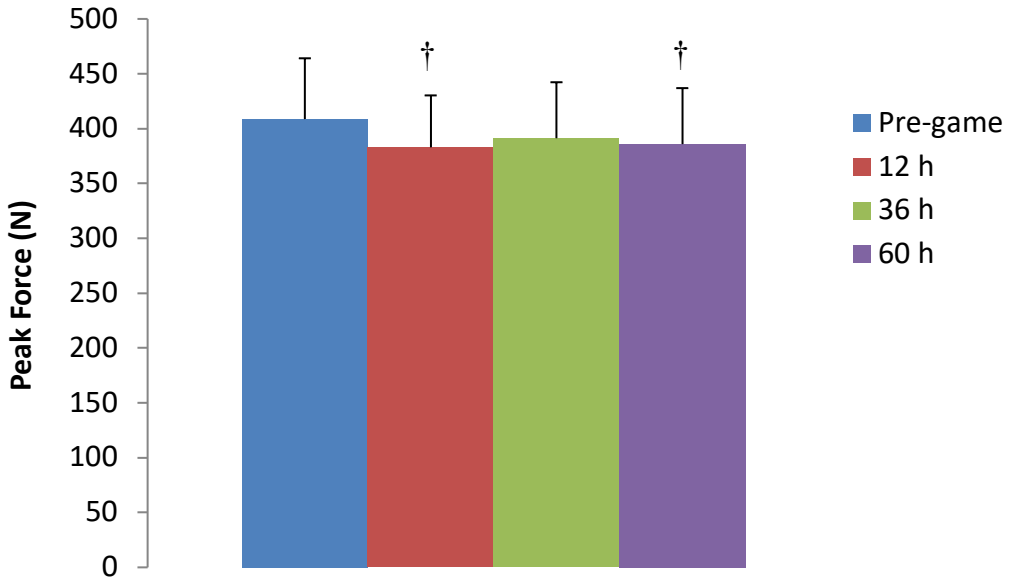

Figure 4. 4 Peak force values pre-game and at 12 h, 36 h and 60 h.

Values are mean ± SD; †p<0.01 vs. pre-game

Sprint speed

Table 4. 3 summarizes the mean 5 m and 20 m sprint times before and after Gaelic football match play. Compared to pre-game values, there was a significant decrease in 5 m and 20 m sprint times at 12 h, 36 h and 60 h.

Table 4. 3 Sprint Performance before and after Gaelic football match play

	Group	
	5 metres	20 metres
Pre-game	0.96 ± 0.04	2.94 ± 0.11
+12 h	1.06 ± 0.06‡	3.12 ± 0.12‡
+36 h+	1.07 ± 0.06‡	3.11 ± 0.11‡
+60 h+	1.07 ± 0.07‡	3.12 ± 0.13‡

Values are mean ± SD, *p<0.05 vs. pre; †p<0.01 vs. pre; ‡p<0.001 vs. pre

CHAPTER 5

DISCUSSION

Gaelic football in an invasion field-based team sport that is very popular among both men and women in Ireland. Like other invasion field-based team sports, Gaelic football is characterized by repeated bouts of eccentric muscle action and frequent high-impact collisions that can result in muscle damage, DOMS and impaired muscle function. In recent years a number of studies have examined the match-play demands and possession characteristics [121,122] of youth Gaelic football. However, no published studies have examined the effect of Gaelic football match-play on biomarkers of muscle damage, inflammation, DOMS and muscle function. The purpose of this study was to examine the effects of competitive Gaelic football game on circulating CK levels, leukocyte trafficking, muscle soreness and muscle function among 17-year club level Gaelic football players.

Recent advances in global positioning systems (GPS) have facilitated a more thorough study of performance during invasion field-based team sports [118]. Indeed, video analysis and player tracking technology are now embedded within the preparation programs and performance evaluation of most elite inter-county Gaelic football teams. In contrast, very little published data is available on the match-play demands during Gaelic football involving youth.

The participants in the present study were well conditioned with on average VO_2 max of 57.97 mL-kg-min^{-1}. An average distance of 6131 m was covered during the 60 min

game. This is very similar to the average distance of 5,774 m covered during 17 games by U-18 players and 5732 m reported during six intercounty U-15 games [122]. It is however, considerably lower than the 8160 m reported in senior elite-intercounty players [123]. More than two-thirds of the total distance covered was spend walking or jogging and only 11% involved either high-speed running or max speed running. Interestingly, the average distance covered per min (100 $m \cdot min^{-1}$) was very similar to that recently reported for elite level senior players (104 $m \cdot min^{-1}$) (McGahan, Burns, Lacey, Gabbett, & Neill, 2018).

CK is the most commonly used biomarker to assess muscle damage in both individual and team sports. In the present study, pre-match CK levels (512 ± 74 U L) were higher than previously reported among prepubescent [124,125], and adolescent males [126]. However, there was large interindividual variability in pregame CK levels with values ranging from 131 to 1641 IU/L (figure 5.1). This equates to a 12.5-fold difference within the squad of players. A study involving a group of 483 male athletes ranging in age from 7 to 44 years reported reference CK levels between 83 to 1043 U/L [16] which also represents a 12.5-fold difference between the lowest and highest CK value. Among Brazilian professional soccer players there was also a degree of variably (200-1600 U/L) in baseline CK levels [127]. In the present study. 9 of the team members had a baseline CK value ≥ 600 IU/L and three players >1000 IU/L. The elevated baseline CK levels may have been due in part to residual muscle damage accumulated from the rigors of the preceding practice session or game. In addition, many of the study participants were involved in a number of

different individual and team sports and, it is therefore possible that the cumulative effect of muscle damage associated with the rigors of training and game participation across multiple sports may have contributed to the elevated baseline CK level.

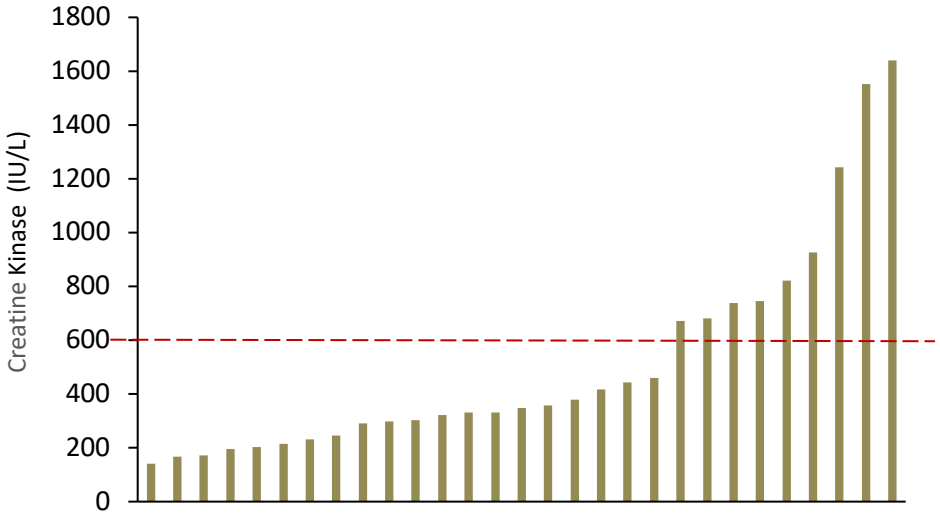

Figure 5. 1 Individual blood CK levels at baseline prior to the game

CK responses to match

Blood levels of CK peaked at 70% above pre-game values at 12 h, and returned to pre-game values at 36 h. The peak CK levels were much higher than those reported in prepubescent and adolescent males following laboratory based studies that involved stepping [128], plyometric jumps [124], concentric contractions of the elbow flexors[129], eccentric contractions of the knee extensor [126,130], bench press [131] downhill running [125] and high intensity treadmill [132] running. They were however, similar to peak values reported in elite 19-year-old rugby league players [54]. It is possible that the true peak CK value may have been missed since for logistical reasons no blood sample was taken between 12 h and 24

h post-game. However, the peak CK level at 12 h was almost identical to values found in 19 year old rugby league players 24 h after a competitive game (874 vs 889 IU/L) [12].

There was no significant relation between any of the measured movement variables and circulating levels of CK in the present study. Our findings do not support a relation between any movement demands variables determined by GPS in Gaelic football and CK plasma activity. Others studies have also failed to find a relation between movement characteristics and CK activity [12,133]. In contrast, Young, Robbins and Hepner, (2012) found a positive association muscle damage and both the distance covered at various speeds and the number of accelerations and decelerations in elite junior level (16-18 y) Australian football players. A positive relation was also found between the number of high intensity movements during soccer and peak CK at 24 post game (Russell et al., 2016).

In addition to high intensity activity involving eccentric muscle action, Gaelic football match play is also synonymous with high impact collisions in the form of tackling and the shoulder charge. The number of tackles and/or high impacts in zone 5 (very heavy) and zone 6 (severe) during rugby union and rugby union match play was found to be associated with peak post-match CK levels (Takarada, 2003, Cunniffe et al., 2010; McLellan, Lovell, & Gass, 2011b). In contrast, there was no association between impacts and postgame CK level in the present study. The fact that the majority of the collisions were in

in Zone 1 (very light) and Zone 2 (light to moderate) indicates that blunt force trauma was not a major contributing factor to the muscle damage.

There was also large interindividual variability in blood CK levels at each time point following the GK game (figure 5.2). It is well established that participant in exercise related studies demonstrate a wide range of physiological responses and it is not uncommon for some participants to experience an adverse response or decline in performance following acute or chronic exercise interventions. Reporting mean changes in CK as a representative of the entire group usually has little relevance for individual players on a sports team and indeed, can often mask adverse responses. In contrast, determining physiologically meaningful changes in CK values on an individual level is of much greater importance in team preparation.

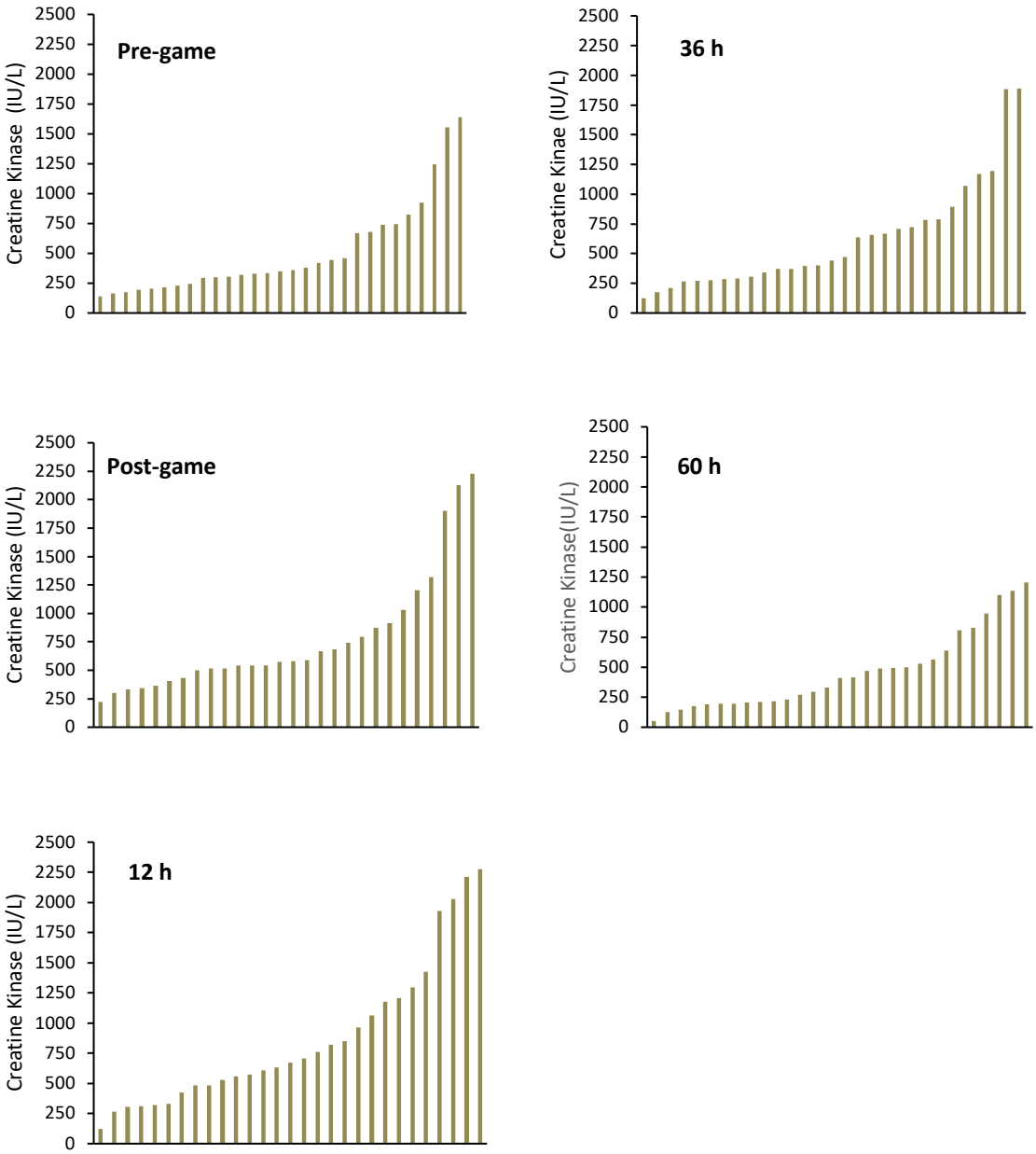

Figure 5. 2 Individual blood CK levels pre-game, post-game and 12 h, 36 h and 60 h during recovery.

Research investigating factors associated with variations in CK response are vital in informing potential measures that could be put in place, to monitor recovery strategies of individual athletes and aid in team selection. In particular, specific gene polymorphisms that influence muscle disruption, calcium handling and inflammatory responses may help to explain the considerable inter-individual variability in the response to muscle damaging exercise [135,136] and warrant further investigation.

DOMS is one of the most common symptoms of EIMD and the associated pain and discomfort can discourage exercise participation and decrease exercise performance. A visual analogue scale that ranged from 0-100 and anchored with written cues was used to assess active muscle soreness. Prior to the game, all of the study participants indicated some degree of muscle soreness, with large interindividual variation (figure 5.3). A little over 50% of the participants had a pre-game muscle soreness value > 20, out a maximal score of 100. This score probably reflects a residual muscle soreness related to previous training sessions and/or games.

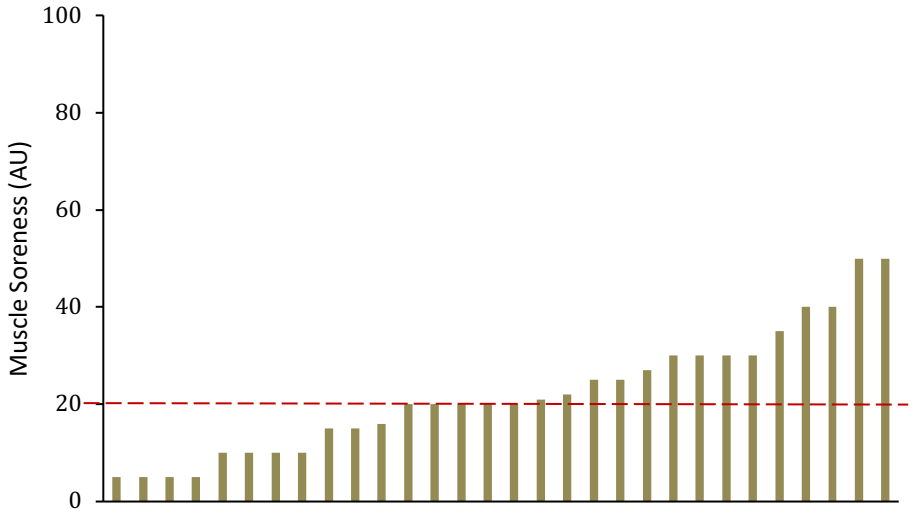

Figure 5. 3 Pre-game individual muscle soreness values

Muscle soreness was significantly elevated at 12 h and 36 h post game and returned to baseline at 60 h. There was large heterogeneity in both absolute and percentage change in muscle soreness. The mean peak muscle soreness value was approximately 1.6-fold higher than at baseline. However, the average peak value of 56 was well below the maximal achievable value of 100 indicating that the players experienced low to moderate levels of muscle damage following participation in the Gaelic football game.

Among 64 elite Australian Football players muscle soreness was found to also be approximately 50% of the maximal attainable the day after the game and progressively declined each for the following 3 days [137]. Studies involving soccer have reported peak muscle soreness at 24 to 48 h post-game [55,138–140]. Although muscle soreness peaked at 12 h and remained elevated above baseline value at 36 h, it is possible that the true peak MS value may have been missed as no measurement was taken between 12 h and 36 h post-

game. There was no significant association between blood CK levels and muscle soreness at any time point before or after the game. Among 17-year old male tennis players, Gomes *et al.*, (2014) found that muscle soreness measured using the VAS scale peaked 24 h after a 3 h game and returned to pre-game values at 48 h. The peak value (18 mm) was much lower that found in the present study (56 mm) mostly like due to the physical nature of invasion team sports compared to tennis match play.

Muscle Performance

Muscular power, defined as the ability to produce force at a rapid velocity of movement is important in activities that rely on jumping, sprinting and rapid change of direction. Peak force development was 6% below the pre-game level 12 h after the game and was still significantly reduced 28 h later (60 h). Compared to pre-games values, both 5 m and 20 m sprint performance were decreased at 12 h, 36 h and 60 h into recovery. There was no associated between blood CK levels and peak force or sprint performance during recovery.

Decrements in peak force development and sprint performance is a commonly experienced phenomenon following competitive match play in elite young athletes playing rugby [110] and elite soccer [56]. Force loss ranging from 10%-65% of pre-exercising values have been reported [109]. Disruption of force-generating and/or force transmitting structures is believed to one of the primary mechanism responsible for the decrements in muscle performance in the days following EIMD.

Inflammation

It is well established that acute exercise results in a biphasic leukocyte response characterized by a leukocytosis comprising all major leukocyte subpopulations during, and immediately following exercise, and a leukocytopenia involving both granulocytes and lymphocytes starting within 4 h of recovery [142]. In the present study, there was a 33% increase in the number of circulating leukocytes immediately post game compared to pre-game. This exercise induced leukocytosis is believed to be mediated by hemodynamic shear stress and/or catecholamines acting on leukocyte beta 2-adrenergic receptors [143]. Contrary to the finding in this study, other studies involving soccer have reported elevations in the blood leukocyte levels that persisted for 24 h to 48 h post game [55].

The sustained leukocytopenia 60 h post game reflects the preferential trafficking of leukocyte subtypes with tissue-migrating potential and potent effector function. The decrease in the circulating leukocytes was due primarily to changes in both granulocytes and lymphocytes. Although granulocyte subpopulations were not measured, it is likely the neutrophils were primarily responsible for the sustained granulocytopenia at 60 h [144,145]. All lymphocyte sub-populations have been shown to contribute to the post exercise lymphopenia, with NK cells the largest contributor [146]. Reduced blood levels of lymphocytes have been reported in men [147] and women [144] following participation in a competitive soccer game.

The transient leukocytopenia at 60 h may indicate some degree of immunodepression that in the absence of appropriate recovery may increase the risk of opportunistic infections and illness in susceptible individuals [148]. Importantly, allowing players to undertake rigorous training or play competitive games while the immune system depressed could lead to more severe immunodepression and illness.

Conclusion

In conclusion, Gaelic football match play involving adolescents results in significant changes in markers of muscle damage, DOMS, circulating leukocytes and muscle function. Effective planning of training and recovery is important in the preparation of Gaelic football teams. In many cases decisions regarding recovery duration and intensity are based solely on player feedback and coaches intuition. The challenge of optimising recovery is further compounded by large inter-individual variability in responses to both training and competitive matches. The measurement of blood biomarkers, muscle soreness, sprint speed and jump performance may allow the coach to individually monitor recovery status.

Limitations

- It was not possible to verify if the study participants refrained from strenuous physical activity for 24 h before the game and for 60 h after the game as requested.
- For logistically reasons it was not possible to collect data between 12 and 36 h post game.

- The game was a specially organised for the purpose of the study and may therefore, have lacked the intensity associated with a competitive fixture.
- Participants were not familiarised with the testing procedures prior to their participation in the study.

Future Research

- To measure resting baseline CK levels in order to establish individualised upper limits of normal to be used as a reference value.
- Identify genetic polymorphisms that could help to explain variability in CK levels between responders and non-responders.
- Assess the relation between deceleration, acceleration, change of direction and muscle damage.
- Assess both indices of both innate and acquired immune function

Bibliography

1. Peake JM, Neubauer O, Gatta PAD, Nosaka K. Muscle damage and inflammation during recovery from exercise. *J Appl Physiol*. 2017;122(3):559-570. doi:10.1152/japplphysiol.00971.2016

2. Hyldahl RD, Hubal MJ. Lengthening our perspective: Morphological, cellular, and molecular responses to eccentric exercise. *Muscle and Nerve*. 2014;49(2):155-170. doi:10.1002/mus.24077

3. Aoi W, Naito Y, Tokuda H, Tanimura Y, Yoshikawa T. Exercise-Induced Muscle Damage Impairs Insulin Signaling Pathway Associated With IRS-1 Oxidative Modification. *Physiol Res*. 2012;8408:81-88.

4. Fielding RA, Frontera WR, Evans WJ, et al. Eccentric exercise-induced muscle damage impairs muscle glycogen repletion Eccentric exercise-induced muscle damage impairs muscle glycogen repletion. *Am Physiol Soc*. 1987;(March 2016).

5. Hortobagyi T, Katch FI. Eccentric and concentric torque-velocity relationships during arm flexion and extension. *Eur J Appl Physiol Occup Physiol*. 1990;60(5):395-401. doi:10.1007/BF00713506

6. Abbott BC, Bigland B, Ritchie JM. The physiological cost of negative work. *J Physiol*. 1952;117(3):380-390. doi:10.1113/jphysiol.1952.sp004755

7. Lieber RL, Fridén J. Mechanisms of muscle injury after eccentric contraction. *J Sci Med Sport*. 1999;2:253-265. doi:10.1016/S1440-2440(99)80177-7

8. Clarkson PM, Byrnes WM, McKormick KM, Turcotte LP, White JS. Muscle soreness and serum creatine kinase activity following isometric , eccentric, and concentric exercise. *Int J Sports Med*. 1986;7(3):152-155.

9. Byrne C, Eston RG, Edwards RH. Characteristics of isometric and dynamic strength loss following eccentric exercise-induced muscle damage. *Scand J Med Sci Sports*. 2001;11(3):134-140. doi:10.1046/j.1524-4725.2001. 110302.x

10. Twist C, Eston R. The effects of exercise-induced muscle damage on maximal intensity intermittent exercise performance. *Eur J Appl Physiol*. 2005;94(5-6):652-658. doi:10.1007/s00421-005-1357-9

11. Hunkin SL, Fahrner B, Gastin PB. Creatine kinase and its relationship with match performance in elite Australian Rules football. *J Sci Med Sport*. 2014;17(3):332-336. doi:10.1016/j.jsams.2013.05.005

12. McLellan CP, Lovell DI, Gass GC. Creatine Kinase and Endocrine Responses of Elite Players Pre, During, and Post Rugby League Match Play. *J Strength Cond Res*. 2010;24(11):2908-2919. doi:10.1519/JSC.0b013e3181c1fcb1

13. Faulkner JAw, Brooks SV OJ. No Title. *Physiother Theory Pract*. 1993;73(12):911-921.

14. Cormack SJ, Newton RU, McGuigan MR. Neuromuscular fatigue and endocrine responses in elite Australian Rules. *Int J Sports Physiol Perform*. 2008;3(March):1-132.

15. Takarada Y. Evaluation of muscle damage after a rugby match with special reference to tackle plays. *Br J Sports Med*. 2003;37(5):416-419. doi:10.1136/bjsm.37.5.416

16. Mougios V. Reference intervals for serum creatine kinase in athletes. *Br J Sports Med*. 2007;41(10):674-678. doi:10.1136/bjsm.2006.034041

17. Frontera WR, Ochala J. Skeletal muscle: a brief review of structure and function. *Calcif Tissue Int*. 2015;96(3):183-195. doi:10.1007/s00223-014-9915-y

18. Raven P, Wasserman D, Squires WJ, Muray T. *Exercise Physiology: An Integrated Approach.* Australia : Wadsworth Cengage Learning, 2013.; 2013.

19. Sweeney HL, Hammers DW. Muscle Contraction. *Cold Spring Harb Perspect Biol*. 2018;10(2). doi:10.1101/cshperspect.a023200

20. Ottenheijm C, Granzier H. Lifting the Nebula : Novel Insights into Skeletal Muscle Contractility. *Int Union Physiol Sci*. 2010;23:304-310. doi:10.1152/physiol.00016.2010

21. Monroy JA, Powers KL, Gilmore LA, Uyeno TA, Lindstedt SL, Nishikawa KC. What Is the Role of Titin in Active Muscle ? *Am Coll Sport Med*. 2012;(18):73-78.

22. Greising SM, Gransee HM, Mantilla CB, Sieck GC. Systems biology of skeletal muscle : fiber type as an organizing principle. *WIREs Syst Biol Med*. 2012;4(October):457-473. doi:10.1002/wsbm.1184

23. Pette D, Staron RS. Myosin Isoforms , Muscle Fiber Types , and Transitions. 2000;509(February):500-509.

24. Frantz C, Stewart KM, Weaver VM, Frantz C, Stewart KM, Weaver VM. The extracellular matrix at a glance The Extracellular Matrix at a Glance. 2010;2010:4195-4200. doi:10.1242/jcs.023820

25. Theocharis AD, Skandalis SS, Gialeli C, Karamanos NK. Extracellular matrix structure ☆. *Adv Drug Deliv Rev*. 2016;97:4-27. doi:10.1016/j.addr.2015.11.001

26. Biology C, Rebbeck RT, Karunasekara Y, et al. The International Journal of Biochemistry Skeletal muscle excitation – contraction coupling : Who are the dancing partners ? *Int J Biochem Cell Biol*. 2014;48:28-38. doi:10.1016/j.biocel.2013.12.001

27. Huxley A, Niedergerke R. Structural Changes in Muscle During Contraction: Interference Microscopy of Living Muscle Fibres. *Nature*. 1954;(173):971-973.

28. Hikida R. Aging changes in satellite cells and their functions. *Curr Aging Sci*. 2011;4(3):279-297.

29. Bareja A, Holt JA, Luo G, et al. Human and Mouse Skeletal Muscle Stem Cells : Convergent and Divergent Mechanisms of Myogenesis. 2014;9(2). doi:10.1371/journal.pone.0090398

30. Morgan JE, Partridge TA. Muscle satellite cells. *Int J Biochem Cell Biol*. 2003;35(8):1151-1156. doi:10.1016/S1357-2725(03)00042-6

31. Zammit PS. Function of the myogenic regulatory factors Myf5 , MyoD , Myogenin and MRF4 in skeletal muscle , satellite cells and regenerative myogenesis. *Semin Cell Dev Biol*. 2017;72:19-32. doi:10.1016/j.semcdb.2017.11.011

32. Holterman CE, Rudnicki M a. Molecular regulation of satellite cell function. *Semin Cell Dev Biol*. 2005;16(4-5):575-584. doi:10.1016/j.semcdb.2005.07.004

33. Asmussen E. Observations on experimental muscular soreness. Acta Rheumatol Scand. *Acta Physiol Scandanavia*. 1956;(2):109-116.

34. Hough T. Ergographic studies in muscular soreness. *Am J Physiol*. 1902;(7):76-92.

35. Armstrong RB. Mechanisms of exercise-induced delayed onset muscular soreness: a brief review. *Med Sci Sport Exerc*. 1984;16(6):529-538.

36. Friden J, Sjostrom M, Ekblom B. A morphological study of delayed muscle soreness. *Experientia*. 1981;(37):506-507.

37. Newham D, Mcphail G, Mills K. Ultrastructural changes after concentric and eccentric contractions of human muscle. *J Neurol Sci*. 1983;61(October):109-122. doi:10.1016/0022-510X(83)90058-8

38. Newham DJ, McPhail G, Millis K.R. ERH. Ultrastructural changes after concentric and eccentric contractions of human muscle. *J Neurol Sci*. 1983;61(1):109-122.

39. Kjær M. Role of Extracellular Matrix in Adaptation of Tendon and Skeletal Muscle to Mechanical Loading. *Physiol Rev*. 2004;84(2):649-698.

40. Stauber W.T. Clarkson P. M. Fritz VK and EWJ. Extracellular matrix disruption and pain after eccentric muscle action. *J Appl Physiol*. 1990;69(3):868-874.

41. Kjær M, Magnusson P, Langberg H. Extracellular matrix adaptation of tendon and skeletal muscle to exercise Tendon and collagen synthesis. *J Anat*. 2006;2:1-5.

42. Peake JM, Suzuki K, Wilson G, et al. Exercise-induced muscle damage, plasma cytokines, and markers of neutrophil activation. *Med Sci Sports Exerc*. 2005;37(5):737-745. doi:10.1249/01.MSS.0000161804.05399.3B

43. Clarkson PM, Hubal MJ. Exercise-Induced Muscle Damage in Humans. *Am J Phys Med Rehabil*. 2002;81(11):52-69. doi:10.1097/01.PHM.0000029772.45258.43

44. Warren GL, Lowe DA AR. Measurement tools used in the study of eccentric contraction-induced injury. *Sport Med*. 1999;27:43-59.

45. Sorichter S. Skeletal muscle injury induced by eccentric muscle action : Muscle proteins as markers of muscle fiber injury. *Exerc immunilogy Rev*.

1999;5(February):5-21.

46. McNeil PL, Khakee R. Disruptions of Muscle Fiber Plasma Membranes Role in Exercise-induced Damage. *Am J Pathol*. 1992;140(5):1097-1109.

47. Lang H, Würzburg U. Creatine kinase, an enzyme of many forms. *Clin Chem*. 1982;28(7):1439-1447. doi:10.1093/clinchem/28.7.1439

48. Brancaccio P, Maffulli N, Limongelli FM. Creatine kinase monitoring in sport medicine. *Br Med Bull*. 2007;81-82(1):209-230. doi:10.1093/bmb/ldm014

49. Cunniffe B, Hore AJ, Whitcombe DM, Jones KP, Baker JS, Davies B. Time course of changes in immuneoendocrine markers following an international rugby game. *Eur J Appl Physiol*. 2010;108(1):113-122. doi:10.1007/s00421-009-1200-9

50. Twist C, Sykes D. Evidence of exercise-induced muscle damage following a simulated rugby league match. *Eur J Sport Sci*. 2011;11(6):401-409. doi:10.1080/17461391.2010.536575

51. Smart DJ, Gill ND, Beaven CM, Cook CJ, Blazevich AJ. The relationship between changes in interstitial creatine kinase and game-related impacts in rugby union. *Br J Sports Med*. 2008;42(3):198-201. doi:10.1136/bjsm.2007.040162

52. Twist C, Waldron M, Highton J, Burt D, Daniels M. Neuromuscular, biochemical and perceptual post-match fatigue in professional rugby league forwards and backs. *J Sports Sci*. 2012;30(4):359-367. doi:10.1080/02640414.2011.640707

53. Russell M, Sparkes W, Northeast J, Cook CJ, Bracken RM, Kilduff LP. Relationships between match activities and peak power output and Creatine Kinase responses to professional reserve team soccer match-play. *Hum Mov Sci*. 2016;45:96-101. doi:10.1016/j.humov.2015.11.011

54. Johnston RD, Gabbett TJ, Seibold AJ, Jenkins DG. Influence of physical contact on neuromuscular fatigue and markers of muscle damage following small-sided games. *J Sci Med Sport*. 2014;17(5):535-540. doi:10.1016/j.jsams.2013.07.018

55. Ispirlidis I, Fatouros IG, Jamurtas AZ, et al. Time-course of changes in inflammatory and performance responses following a soccer game. *Clin J Sport Med*. 2008;18(5):423-431. doi:10.1097/JSM.0b013e3181818e0b

56. Fatouros IG, Chatzinikolaou A, Douroudos II, et al. Time-Course of Changes in Oxidative Stress and Antioxidant Status Responses Following a Soccer Game. *J Strength Cond Res*. 2010;24(12):3278-3286. doi:10.1519/JSC.0b013e3181b60444

57. Djaoui L, Garcia JDC, Hautier C, Dellal A. Kinetic post-match fatigue in professional and youth soccer players during the competitive period. *Asian J Sports Med*. 2016;7(1). doi:10.5812/asjsm.28267

58. Russell M, Northeast J, Atkinson G, et al. Between-Match Variability of Peak Power Output and Creatine Kinase Responses to Soccer Match-Play. *J Strength Cond Res*. 2015;29(8):2079-2085. doi:10.1519/JSC.0000000000000852

59. Naedlec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in Soccer:

Part I-post-match fatigue and time course of recovery. *Sport Med*. 2012;42(12):997-1015. doi:10.2165/11635270-000000000-00000

60. Young WB, Robbins DW, Hepner J. Movements Demands in Australian Rules Football as Indicators of Muscle Damage. *J Strength Cond Res*. 2012;26(2):492-496. doi:10.1519/JSC.0b013e318225a1c4

61. Johnston RD, Gabbett TJ, Jenkins DG. Influence of an intensified competition on fatigue and match performance in junior rugby league players. *J Sci Med Sport*. 2012;16(5):460-465. doi:10.1016/j.jsams.2012.10.009

62. Coutts AJ, Reaburn P, Piva TJ, Rowsell GJ. Monitoring for overreaching in rugby league players. *Eur J Appl Physiol*. 2007;99(3):313-324. doi:10.1007/s00421-006-0345-z

63. Kraemer WJ, Looney DP, Martin GJ, et al. Changes in creatine kinase and cortisol in national collegiate athletic association division I american football players during a season. *J strength Cond Res*. 2013;27(2):434-441. doi:10.1519/JSC.0b013e318281d1b0

64. Newham DJ, Jones DA, Toifree SEJ, Edwards RHT. Skeletal muscle damage : a study of isotope uptake , enzyme efflux and pain after stepping. *Eur J Appl Physiol*. 1986;(55):106-112.

65. Clarkson PM, Hoffman EP, Zambraski E, et al. ACTN3 and MLCK genotype associations with exertional muscle damage. *J Appl Physiol*. 2005;99(4):564-569. doi:10.1152/japplphysiol.00130.2005.

66. Nosaka K, Clarkson PM. Muscle damage following repeated bouts of high force eccentric exercise. *Med Sci Sport Exerc*. 1995;(9).

67. Armstrong RB. Initial events in muscle damage from exercise. *Med Sci Sport Exerc*. 1990;22(4):431-435.

68. Morgan D, Allen D. Early events in stretch-induced muscle damage. *J Appl Physiol*. 1999;138(3):2007-2015. doi:10.1016/j.envpol.2004.10.021

69. Friden J, Kjorell U, Thornell LE. Delayed muscle soreness and cytoskeletal alterations: An immunocytological study in man. *Int J Sports Med*. 1984;5(1):15-18. doi:10.1055/s-2008-1025873

70. Mackey AL, Brandstetter S, Schjerling P, et al. Sequenced response of extracellular matrix deadhesion and fibrotic regulators after muscle damage is involved in protection against future injury in human skeletal muscle. *FASEB J*. 2011;25(6):1943-1959. doi:10.1096/fj.10-176487

71. Clarkson PM, Nosaka K, Braun B. Muscle function after exercise-induced muscle damage and rapid adaptation. *MedSciSports Exerc*. 1992;24(5):512-520.

72. Warren GL, Lowe DA, Armstrong RB. Measurement tools used in the study of eccentric contraction-induced injury. *Sport Med*. 1999;27(1):43-59.

73. Nosaka K, Newton M, Sacco P. Delayed-onset muscle soreness does not reflect the

magnitude of eccentric exercise-induced muscle damage. *Scand J Med Sci Sport*. 2002;12(6):337-346. doi:10.1034/j.1600-0838.2002.10178.x

74. Hyldahl RD, Xin L, Hubal MJ, Moeckel-cole S, Chipkin S, Clarkson PM. Activation of nuclear factor- kB following muscle eccentric contractions in humans is localized primarily to skeletal muscle-residing pericytes. *FASEB J*. 2011;5:2956-2966. doi:10.1096/fj.10-177105

75. Tidball JG, Villalta SA. Regulatory interactions between muscle and the immune system during muscle regeneration. *Am J Regul Intergartive Comp Physiol*. 2010;298(5):1173-1187. doi:10.1152/ajpregu.00735.2009.

76. Dray A, Perkins M. Bradykin and inflammatory pain. *Trends Neurosci*. 1993;16(3):99-104.

77. Geppetti P. Sensory neuropeptide release by bradykinin : mechanisms and pathophysiological implications. *Regul Pept*. 1993;47:1-23.

78. Woolf C, Garabedian S, Ma Q, Crilly P, Winter J. Nerver Growth Factor Contributes to the Generation of Inflammatory Sensory Hypersensitivity. *Neuroscience*. 1994;62(2):327-331.

79. Friden J, Sfakianos PN, Hargens AR, Akeson WH. Residual Muscular Swelling After Repetitive Eccentric Contractions. *J Orthop Res*. 1988;(6):493-498.

80. Nieman DC, Pedersen BK. Exercise and immune function. *Sport Med*. 1999;27(2):73-80.

81. Mackinnon LT. Chronic exercise training effects on immune function. *Med Sci Sport Exerc*. 2000;32(7). https://journals.lww.com/acsm-msse/Fulltext/2000/07001/Chronic_exercise_training_effects_on_immune.1.aspx.

82. Nieman DC. Immune response to heavy exertion. *J Appl Physiol*. 1997;82(5):1385-1394. doi:10.1152/jappl.1997.82.5.1385

83. Smith LL. Acute inflammation: the underlying mechanism in delayed onset muscle soreness? *Med Sci Sports Exerc*. 1991;23(5):542-551.

84. Brigitte M, Schilte C, Plonquet A, et al. Muscle resident macrophages control the immune cell reaction in a mouse model of notexin-induced myoinjury. *Arthritis Rheum*. 2010;62(1):268-279. doi:10.1002/art.27183

85. Warren GL, Hulderman T, Jensen N, et al. Physiological role of tumor necrosis factor α in traumatic muscle injury. *FASEB J*. 2002;(8):1630-1632.

86. Cheng M, Nguyen MH, Fantuzzi G, Koh TJ. Endogenous interferon-γ is required for efficient skeletal muscle regeneration. *Am J Physiol - Cell Physiol*. 2008;294(5). doi:10.1152/ajpcell.00568.2007

87. Collins RA, Grounds MD. The Role of Tumor Necrosis Factor-alpha (TNF-α) in Skeletal Muscle Regeneration. *J Histochem Cytochem*. 2011;49(8):989-1001. doi:10.1177/002215540104900807

88. Chen SE, Gerken E, Zhang Y, et al. Role of TNF-α signaling in regeneration of cardiotoxin-injured muscle. *Am J Physiol - Cell Physiol*. 2005;289(5 58-5). doi:10.1152/ajpcell.00062.2005

89. Hawke TJ, Garry DJ. Myogenic satellite cells: physiology to molecular biology. *J Appl Physiol*. 2001;91(2):534-551. doi:10.1152/jappl.2001.91.2.534

90. St. Pierre BA, Tidball JG. Macrophage activation and muscle remodeling at myotendinous junctions after modifications in muscle loading. *Am J Pathol*. 1994;145(6):1463-1471.

91. Villalta SA, Rinaldi C, Deng B, Liu G, Fedor B, Tidball JG. Interleukin-10 reduces the pathology of mdx muscular dystrophy by deactivating M1 macrophages and modulating macrophage phenotype. *Hum Mol Genet*. 2011;20(4):790-805. doi:10.1093/hmg/ddq523

92. Mantovani A, Sica A, Sozzani S, Allavena P, Vecchi A, Locati M. The chemokine system in diverse forms of macrophage activation and polarization. *Trends Immunol*. 2004;25(12):677-686. doi:10.1016/j.it.2004.09.015

93. O'Neill L, Hardie D. Metabolism of inflammation limited by AMPK and pseudo-starvation. *Nature*. 2013;(493):346-355.

94. LeGrand F, Rudnicki MA. Skeletal muscle satellite cells and adult myogenesis. *Curr Opin Cell Biol*. 2007;19(6):628-633. doi:10.1016/j.pestbp.2011.02.012.Investigations

95. Grounds MD, Garrett KL, Lai MC, Wright WE, Beilharz MW. Identification of skeletal muscle precursor cells in vivo by use of MyoD1 and myogenin probes. *Cell Tissue Res*. 1992;267(1):99-104. doi:10.1007/BF00318695

96. Black OB, Molkentin J. Cooperative activation of muscle gene expression by MEF2 and myogenic BHLH proteins. E. *FASEB J*. 1996;10(6):1125-1136.

97. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev*. 2001;81(4):1725-1789. doi:10.1152/physrev.2001.81.4.1725

98. Gibala MJ, MacDougall JD, Tarnopolsky MA, Stauber WT, Elorriaga A. Changes in human skeletal muscle ultrastructure and force production after acute resistance exercise. *J Appl Physiol*. 1995;78(2):702-708. doi:10.1152/jappl.1995.78.2.702

99. Newham DJ, Jones DA, Clarkson PM. Repeated high-force eccentric exercise: effects on muscle pain and damage. *J Appl Physiol*. 1987;63(4):1381-1386. doi:10.1152/jappl.1987.63.4.1381

100. Newham DJ, Jones DA, Ghosh G, Aurora P. Muscle fatigue and pain after eccentric contractions at long and short length. *Clin Sci*. 1988;74(5):553-557. doi:10.1042/cs0740553

101. Persson M, Steinz MM, Westerblad H, Lanner JT, Rassier DE. Force generated by myosin cross-bridges is reduced in myofibrils exposed to ROS/RNS. *Am J Physiol Physiol*. 2019;317(6):C1304-C1312. doi:10.1152/ajpcell.00272.2019

102. Markovic G, Dizdar D, Jukic I, Cardinale M. Reliability and Factorial Validity of Squat and Countermovement Jump Tests. *J Strength Cond Res*. 2004;18(3):551-555. doi:10.1519/00124278-200408000-00028

103. Pueo B, Lipinska P, Jiménez-Olmedo JM, Zmijewski P, Hopkins WG. Accuracy of Jump-Mat Systems for Measuring Jump Height. *Int J Sports Physiol Perform*. 2017;12(7):959-963. doi:10.1123/ijspp.2016-0511

104. Castagna C, Ganzetti M, Ditroilo M, Giovannelli M, Rocchetti A, Manzi V. Concurrent Validity of Vertical Jump Performance Assessment Systems. *J Strength Cond Res*. 2013;27(3):761-768. doi:10.1519/JSC.0b013e31825dbcc5

105. Balsalobre-Fernández C, Glaister M, Lockey RA. The validity and reliability of an iPhone app for measuring vertical jump performance. *J Sports Sci*. 2015;33(15):1574-1579. doi:10.1080/02640414.2014.996184

106. Morgan DL. New insights into the behavior of muscle during active lengthening. *Biophys J*. 1990;57(2):209-221. doi:10.1016/S0006-3495(90)82524-8

107. Warren GL, Ingalls CP, Lowe DA, Armstrong RB. What Mechanisms Contribute to the Strength Loss That Occurs During and in the Recovery from Skeletal Muscle Injury ? *J Orthop Sport Phys Ther*. 2002;(1).

108. Warren BYGL, Lowe DA, Hayes DA, Karwoski CJ, Prior BM, Armstrong RB. Excitation failure in eccentric contraction-induced injury of mouse soleus muscle. *J Physiol*. 1993:487-499.

109. Hubal MJ, Rubinstein SR, Clarkson PM. Mechanisms of Variability in Strength Loss after Muscle-Lengthening Actions. *MedSciSports Exerc*. 2007;39(19):461-468. doi:10.1249/01.mss.0000247007.19127.da

110. McLellan CP, Lovell DI. Neuromuscular Responses to Impact and Collision During Elite Rugby League Match Play. *J Strength Cond Res*. 2012;26(5):1431-1440. doi:10.1519/JSC.0b013e318231a627

111. Andersson H, Raastad T, Nilsson J, Paulsen G, Garthe I, Kadi F. Neuromuscular fatigue and recovery in elite female soccer: Effects of active recovery. *Med Sci Sports Exerc*. 2008;40(2):372-380. doi:10.1249/mss.0b013e31815b8497

112. Horita T, Komi P V., Nicol C, Kyr��inen H. Effect of exhausting stretch-shortening cycle exercise on the time course of mechanical behaviour in the drop jump: possible role of muscle damage. *Eur J Appl Physiol*. 1999;79(2):160-167. doi:10.1007/s004210050490

113. Johnston RD, Gibson N V., Twist C, Gabbett TJ, MacNay SA, MacFarlane NG. Physiological responses to an intensified period of rugby league competition. *J Strength Cond Res*. 2013;27(3):1. doi:10.1519/JSC.0b013e31825bb469

114. Thorlund J, Aagaard P, Madsen K. Rapid Muscle Force Capacity Changes after Soccer Match Play. *Int J Sports Med*. 2009;30(04):273-278. doi:10.1055/s-0028-1104587

115. Highton JM, Twist C, Eston RG. The effects of exercise-induced muscle damage on agility and sprint running performance. *J Exerc Sci Fit*. 2009;7(1):24-30.

doi:10.1016/S1728-869X(09)60004-6

116. Semark A, Noakes TD, St Clair Gibson A, Lambert MI. The effect of a prophylactic dose of flurbiprofen on muscle soreness and sprinting performance in trained subjects. *J Sport Sci*. 1999;(17):197-203.

117. Sweeting AJ, Cormack SJ, Morgan S, Aughey RJ, Edouard P. When Is a Sprint a Sprint ? A Review of the Analysis of Team-Sport Athlete Activity Profile. 2017;8(June):1-12. doi:10.3389/fphys.2017.00432

118. Jennings D, Cormack S, Coutts AJ, Boyd L, Aughey RJ. The Validity and Reliability of GPS Units for Measuring Distance in Team Sport Specific Running Patterns. *Int J Sports Physiol Perform*. 2010;(5):328-341.

119. Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. *J Sci Med Sport*. 2010;13(1):133-135. doi:10.1016/j.jsams.2008.09.015

120. Wong DP, Wong SH. Physiological Profile of Asian Elite Youth Soccer Players. *J Strength Cond Res*. 2009;23(5):1383-1390. doi:10.1519/JSC.0b013e3181a4f074

121. Cullen BD, Roantree MT, McCarren AL, et al. Physiological Profile and Activity Pattern of Minor Gaelic Football Players. *J Strength Cond Res*. 2017;31(7):1811-1820. doi:10.1519/JSC.0000000000001667

122. Reilly B, Akubat I, Lyons M, Collins DK. Match-play demands of elite youth Gaelic football using global positioning system tracking. *J Strength Cond Res*. 2015;29(4):989-996. doi:10.1519/jsc.0000000000000714

123. Mcgahan J, Burns C, Lacey S, Gabbett T, Neill CO. An investigation in to the positional running demands of elite Gaelic football players: how competition data can inform training practice. *J strength Cond Res*. 2018. doi:10.1519/JSC.0000000000002492

124. Marginson V, Rowlands A V, Gleeson NP, Eston RG, Rowlands A V, Gleeson NP. Comparison of the symptoms of exercise-induced muscle damage after an initial and repeated bout of plyometric exercise in men and boys. *J Appl Physiol*. 2005;99(3):1174-1181. doi:10.1152/japplphysiol.01193.2004.

125. Webber LM, Byrnes WC, Rowland TW, Foster VL. Serum creatine kinase activity and delayed muscle soreness in prepubescent children: A perliminsry Study. *Pediatr Exerc Sci*. 1989;1(4):351-359.

126. Pullinen T, Mero A, Huttunen P, Pakarinen A, Komi P V. Resistance exercise-induced hormonal response under the influence of delayed onset muscle soreness in men and boys. *Scand J Med Sci Sports*. 2011;21(6):184-194. doi:10.1111/j.1600-0838.2010.01238.x

127. Lazarim FL, Antunes-Neto JMF, da Silva FOC, et al. The upper values of plasma creatine kinase of professional soccer players during the Brazilian National Championship. *J Sci Med Sport*. 2007;12(1):85-90. doi:10.1016/j.jsams.2007.10.004

128. Duarte JA, Magalhes J. ., Monteirol L, Soaresl JM., Appell H-J. Exercise-Induced Signs of Muscle Overuse in Children. *Int J Sport Med*. 1999;20(2):103-108.

129. Chen TC, Chen HL, Liu YC, Nosaka K. Eccentric exercise-induced muscle damage of pre-adolescent and adolescent boys in comparison to young men. *Eur J Appl Physiol*. 2014;114(6):1183-1195. doi:10.1007/s00421-014-2848-3

130. Deli CK, Fatouros IG, Paschalis V, et al. A Comparison of Exercise-Induced Muscle Damage Following Maximal Eccentric Contractions in Men and Boys. *Pediatr Exerc Sci*. 2017.

131. Soares JMC, Mota P, Duarte JA, Appell HJ. Children Are Less Susceptible to Exercise-Induced Muscle Damage Than Adults : A Preliminary Investigation. *Pediatr Exerc Sci*. 1996;8(4):361-367.

132. Pal S, Chaki B, Chattopadhyay S, Bandyopadhyay A. High intensity exercise induced oxidative stress and skeletal muscle damage in post-pubertal boys and girls. *J Strength Cond Res*. 2017:1. doi:10.1519/JSC.0000000000002167

133. Scott A, Malone J, Morgans R, et al. The relationship between physical match performance and 48-h post-game creatine kinase concentrations in English Premier League soccer players. *Int J Sports Sci Coach*. 2016;11(6):846-852. doi:10.1177/1747954116676111

134. McLellan CP, Lovell DI, Gass GC. Biochemical and endocrine responses to impact and collision during elite rugby league match play. *J Strength Cond Res*. 2011;25(6). doi:10.1519/JSC.0b013e3181db9bdd

135. Yamin C, Duarte JAR, Oliveira JMF, et al. IL6 (-174) and TNFA (-308) promoter polymorphisms are associated with systemic creatine kinase response to eccentric exercise. *Eur J Appl Physiol*. 2008;104(3):579-586. doi:10.1007/s00421-008-0728-4

136. Hoffman EP, Gordish-Dressman H, mMcLane VD, et al. Alterations in Osteopontin Modify Muscle Size in Females in Both Humans and Mice. *Med Sci Sport Exerc*. 2013;45(6):1060-1068. doi:10.1249/MSS.0b013e31828093c1

137. Montgomery PG, Hopkins WG. The Effects of Game and Training Loads on Perceptual Responses of Muscle Soreness in Australian Football. 2013:312-318.

138. Fatouros IG, Jamurtas AZ. Insights into the molecular etiology of exercise-induced inflammation: Opportunities for optimizing performance. *J Inflamm Res*. 2016;9:175-186. doi:10.2147/JIR.S114635

139. Rampinini E, Bosio A, Ferraresi I, Petruolo A, Morelli A, Sassi A. Match-related fatigue in soccer players. *Med Sci Sports Exerc*. 2011;43(11):2161-2170. doi:10.1249/MSS.0b013e31821e9c5c

140. Silva JR, Rebelo A, Ascensão A, Magalhães J, Marques F, Seabra A. Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. *Eur J Appl Physiol*. 2013;113(9):2193-2201. doi:10.1007/s00421-013-2633-8

141. Gomes R V., Santos RCO, Nosaka K, Moreira A, Miyabara EH, Aoki MS. Muscle damage after a tennis match in young players. *Biol Sport*. 2014;31(1):27-32. doi:10.5604/20831862.1083276

142. Peake JM, Neubauer O, Walsh NP, Simpson RJ. Recovery of the immune system after exercise. *J Appl Physiol*. 2017;122(5):1077-1087. doi:10.1152/japplphysiol.00622.2016

143. Walsh NP, Gleeson M, Shephard RJ, et al. Position statement. Part one: Immune function and exercise. *Exerc Immunol Rev*. 2011;17:6-63. http://www.ncbi.nlm.nih.gov/pubmed/21446352.

144. Leyre G, Fátima R, Jose AL, Irazusta J, Gil SM. Metabolic impact of a soccer match on female players. *J Sports Sci*. 2011;29(12):1345-1352. doi:10.1080/02640414.2011.597420

145. Peake JM. Exercise-induced alterations in neutrophil degranulation and respiratory burst activity: possible mechanisms of action. *Exerc Immunol Rev*. 2002;8(9):49-100. http://www.ncbi.nlm.nih.gov/pubmed/12690938.

146. Shek P, Sabiston B, Buguet A, Radomski M. Strenuous Exercise and Immunological Changes. *Int J Sports Med*. 1995;16(07):466-474. doi:10.1055/s-2007-973039

147. Magalhães J, Rebelo A, Oliveira E, Silva JR, Marques F, Ascensão A. Impact of Loughborough Intermittent Shuttle Test versus soccer match on physiological, biochemical and neuromuscular parameters. *Eur J Appl Physiol*. 2010;108(1):39-48. doi:10.1007/s00421-009-1161-z

148. Pedersen BK, Rohde T, Ostrowski K. Recovery of the immune system after exercise. *Acta Physiol Scand*. 1998;162(3):325-332. doi:10.1046/j.1365-201X.1998.0325e.x