The Assessment of Exercise-Induced Muscle Damage - Evaluation of Exercise Mode and Environment

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Impact of COVID-19

The Covid-19 pandemic impacted upon the final research conducted and presented in this thesis (section 7). In response to the pandemic the University suspended all face-to-face research in March 2020. At this point ethical approval for the research had been received and data collection was due to commence.

The planned research was due to extend on the research in section 5 and investigate recovery following an exercise class. The workout was to be completed in a group environment and delivered by a certified fitness instructor. Recovery responses were to be compared between four groups: 1) physically active accustomed to exercise mode 2) physically active unaccustomed to exercise mode 3) physically inactive 4) control; assessed using functional (power, reactive strength, balance) and self-reported (muscle soreness, readiness to exercise) outcomes, over a 48 h period. This investigation would have provided insight into how training status impacts recovery and assisted in informing recovery strategies and motivations to exercise, in the days post regular exercise activities.

As it became apparent that the suspension of face-to-face research would be prolonged, the decision was taken to redesign the final study (section 7). To enable the research to take place the study was designed so it could be completed remotely, by individuals in their own homes. The study design was modified and ethical approval received to investigate recovery from a virtual exercise class, with physically active and inactive individuals. Therefore, it was not possible to incorporate physical or functional outcomes to monitor recovery from exercise. This shifted the focus of the research to comparing self-reported outcomes (muscle soreness, readiness to exercise, fatigue, exertion) up to 48 h post exercise. This provided initial insight into how the recovery needs compare between active and inactive individuals. However, further investigation is now warranted (as initially intended), to include physical / functional outcomes and additional groups (i.e., physical active accustomed, physically active not accustomed & control). This would provide support for the current findings and additional insight into the recovery needs of active and inactive individuals, following regular exercise activities.

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Abstract

It is well established that performing unaccustomed exercise is associated with causing muscle damage. Historically, recovery from muscle damaging exercise has been investigated using laboratory-based eccentrically biased modes of exercise and recovery assessed using conventional indirect indicators. Recently, there has been a shift to investigating muscle damage following exercise representative of competitive sport environments, including functional and psychological assessments to monitor recovery.

This thesis investigated how the mode of exercise and environment in which it is conducted, affect the muscle damage response. A review of the literature led to three main research areas: 1) Does conventional muscle damaging exercise impair functional and psychological outcomes? 2) Do common day-to-day exercise activities result in muscle damage? 3) How does muscle damage and recovery compare between conventional and novel modes of exercise?

Completing a conventional muscle damaging mode of exercise (downhill running), impaired functional and psychological outcomes; associations suggested these outcomes may provide proxy indicators for muscle damage. Completing a common exercise activity (exercise class) did not result in muscle damage, however, it impaired reactive strength and readiness to exercise. When compared, conventional muscle damaging exercise caused greater muscle damage than a regular exercise activity; contrasting effects were observed for differences in balance and reactive strength. Less difference was observed in readiness to exercise, with both exercise modes leading individuals to feel less ready. The final investigation, suggested physically active and inactive individuals recover similarly following a common day-to-day exercise activity

The findings presented highlight how recovery from a regular day-to-day exercise mode is different to conventional muscle damaging mode of exercise. A holistic approach, including a specific cluster of assessments, may be more appropriate and accessible, to enable recovery from regular exercise to be accurately monitored. Further research is warranted into the recovery of inactive individuals, to address potential barriers to exercise.

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Abbreviations

ANCOVA	Analysis of Covariance
ANOVA	Analysis of Variance
ARSS	Acute Recovery Stress Scale
CK	Creatine Kinase
CMJ	Countermovement Jump
DJ	Drop Jump
DOMS	Delayed Onset Muscle Soreness
DR	Downhill Running
EB	Emotional Balance
EC	Exercise Class
E-C	Excitation-Contraction
EIMD	Exercise-Induced Muscle Damage
EMM	Estimated Marginal Mean
HR	Heart Rate
IXT	Incremental Exercise Test
LOA	Lack of Activation
LDH	Lactate Dehydrogenase
LIST	Loughborough Intermittent Shuttle Test

Mb	Myoglobin
MPC	Mental Performance Capability
MRI	Magnetic Resonance Imaging
MS	Muscular Stress
MVIC	Maximal Voluntary Isometric Contraction
NES	Negative Emotional State
OR	Overall Recovery
OS	Overall Stress
POMS	Profile of Mood States
PPC	Physical Performance Capability
PPT	Pressure Pain Threshold
RBE	Repeated Bout Effect
RESTQ-Sport	Recovery-Stress Questionnaire for Athletes
RMCORR	Repeated Measures Correlation
ROF	Rating of Fatigue
ROM	Range of Movement
RPE	Rating of Perceived Exertion
RS	Reactive Strength
RSI	Reactive Strength Index
RSR	Reactive Strength Ratio

SEBT	Star Excursion Balance Test
SJ	Squat Jump
SRSS	Short Recovery Stress Scale
VAS	Visual Analogue Scale
WEMWBS	The Warwick-Edinburgh Mental Wellbeing Scale
YBT	Y-Balance Test

1. Literature Review

1.1 Introduction

The concept of muscle soreness following unfamiliar strenuous exercise was first described by Hough back in 1900 (1). Since then it has become well established that completing unaccustomed exercise is associated with causing muscle damage (2). This muscle damaging exercise and the subsequent observed symptoms have been referred to in the scientific literature as “exercise-induced muscle damage” (EIMD). It has been well documented that eccentric (lengthening) muscle actions result in a greater degree of muscle damage, compared to concentric (shortening) or isometric (static) actions (3). The majority of direct and indirect evidence, supports that eccentric actions are the primary source of muscle damage during exercise (4). Muscle damage following eccentric muscle actions result in a rapid adaptation, which stimulates muscle growth and provides a protective effect from subsequent similar exercise activities. This adaptation is known as “the repeated bout effect” (RBE) and attenuates the muscle damage response following a subsequent similar bout of exercise (3-5).

There has been extensive debate into the underlying mechanisms responsible for EIMD, however, these remain not entirely understood (2-4, 6-9). Competing theories have been put forward to explain EIMD and it is generally acknowledged that this occurs through two phases, involving a primary and a secondary damage response (6, 7, 9). In exercise involving eccentric contractions it is proposed that mechanical loading of the muscle is responsible for the initial phase of muscle damage (8, 9). The exact extent to which factors contribute to the initial response remains debated, however, it is believed to begin with damage to the sarcomere, leading to membrane damage, which results in failure of the excitation-contraction (E-C) coupling process (3, 8-10). The non-uniform lengthening of sarcomeres under tension leads to “popping”, increasing tension on passive structures (3, 7-9, 11, 12). Subsequent repetition of this process leads to structural damage, resulting in E-C coupling dysfunction (3, 8-10). Following the primary phase there is a secondary damage response due to a loss of calcium homeostasis, leading to further cell damage (8, 9). This results in a cascade of inflammatory events which ultimately lead to the adaptation and regeneration of the muscle tissue (7, 9).

The direct assessment of muscle damage is challenging, as it requires invasive analysis of muscle biopsies or the use of magnetic resonance imaging (MRI) (4). Muscle biopsies are limited as they only assess the section of muscle where they are obtained and the use of MRI requires extremely expensive equipment, often limited in availability outside of medical institutions. This has led to the majority of research using indirect markers to quantify the magnitude and time-course of muscle damage (3, 4). A decline in the ability of the muscles to generate force is considered the most valid and reliable “gold standard” indirect assessment for EIMD (13). Muscle soreness, myofibrillar proteins and range of motion, present additional measures which have been frequently used in the indirect assessment of EIMD (2-4, 13).

More recently, muscle damage research has begun to include functional assessments (e.g., agility, balance, reactive strength (RS)) (14-16). These functional outcomes may be more applicable to real world sport and exercise scenarios compared to conventional indirect markers of muscle damage. Understanding functional capability may provide greater specificity when determining if an athlete is in a suitable condition to compete or indicate how they are likely to perform (17-22). Equally, understanding how a regular day-to-day exerciser is recovering functionally, may assist in the appropriate selection of subsequent exercise activities, reducing the risk for injury while maximising the potential benefits from training. Further insight into how functional outcomes respond following specific exercise modes, will inform how they may be used to monitor muscle damage and recovery. Many of these functional measures are already used to monitor athletic performance and are reliable when used with healthy adults (23). Therefore, functional outcomes may be more accessible compared to conventional indirect indicators, when monitoring muscle damage and recovery in conventional exercise settings (e.g., gyms/leisure centres).

Currently, it appears no muscle damage research is considering psychological recovery and how this may affect an individual's readiness to conduct further sport/exercise. To take a more holistic approach to recovery from muscle damaging exercise, there is a need to consider not only physical manifestations but also how psychological outcomes may be impaired in response to muscle damaging exercise (24).

Research has traditionally investigated the muscle damage response using laboratory-based protocols involving eccentric actions of isolated muscle groups (e.g., elbow flexors) or exercise biased towards the eccentric phase of muscle action (e.g., downhill running (DR) (25, 26). These traditional modes of exercise, which are biased towards the eccentric phase of muscle action, do not reflect exercise as it is usually completed in conventional sport and exercise settings. In recent years, research has begun to examine the muscle damage response following activities more representative of those undertaken in day-to-day sport and exercise (e.g., sprinting, dance, basketball) (15, 16, 27, 28). Research often utilises laboratory-based artificial modes of exercise, incorporating a large amount of eccentric exercise, to test the efficacy of recovery strategies (29-33). Therefore, if a specific sport or exercise mode, does not result in the same muscle damage response as these extreme eccentrically biased exercise protocols, it is unlikely recovery strategies will be prescribed appropriately. Understanding the sport/exercise specific muscle damage response, will allow recovery strategies to be tailored specifically, facilitating enhanced recovery.

The purpose of this literature review is to broadly investigate the contemporary literature relating to muscle damage which occurs as a result of exercise. This review aims to identify how the mode of exercise affects EIMD and what markers can be used to identify and monitor the muscle damage response. The emergent evidence base will then be reviewed and analysed to identify and discuss the key concepts. The analysis of the evidence base will inform the formation of the research questions to be investigated in this thesis.

1.2 Methods

The literature search conducted for this review was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (34). An extensive search of the literature was conducted before the results were synthesised for inclusion in this review. The purpose of this literature search was to identify research investigating the response to and recovery from EIMD. Additionally, the search aimed to identify the modes of exercise and outcomes being used to induce and assess these responses.

An extensive search was conducted using the CINAHL, Medline, PubMed, SPORT Discus and Web of Science databases, between January 1st, 2008 and September 30th, 2018; an updated search was completed to include between 1st October 2018 and 31st July 2020. The purpose of these time limiters was to identify the key concepts in contemporary research. The search term “EIMD or Exercise-Induced Muscle Damage” was used in conjunction with each of the following terms: “delayed onset muscle soreness (DOMS) or inflammation”, “force or neuromuscular function”, “strength or power”, “balance”, “range of movement (ROM) or flexibility”, “functional”, “psychological” and “blood markers”. Force, muscle soreness, blood markers and ROM were included with their synonyms as these had been identified as markers commonly used to monitor the response to muscle damaging exercise (3, 4, 13). Functional, power and balance were included with synonyms as these had been identified as emerging outcomes being used to investigate EIMD (16). “Psychological” was included as this appeared a gap within the EIMD literature.

Only studies published in peer reviewed journals were considered for inclusion as these have been subjected to a rigorous review process, ensuring a high standard of evidence. Study selection involved a review of article titles, followed by review of abstracts and then a review of full text articles. Following this reference lists were screened and additional seminal papers were included not identified by the initial literature search. Specific criteria were used to determine if studies were eligible for inclusion. Studies were excluded if they were not in English language to ensure language was not a barrier to clear interpretation. To identify research findings which would be applicable to the adult general population, participants were required to be human, healthy and aged between 18-65 years. Studies administering recovery interventions, the use of supplements or training regimes were excluded as these did not align with the focus of this literature search, which was solely on the response to muscle damaging exercise. Research exploring the underlying mechanisms which cause EIMD were excluded as these were beyond the scope of this review.

1.3 Results

The literature search (Figure 1-1) identified a total of 604 papers from all sources. Following the screening of titles and abstracts, full text articles (n = 125) were considered for eligibility. Full text screening led to the exclusion of additional papers (n = 11), the remaining articles (n = 114) were included in the qualitative synthesis and the key findings presented in this review. The qualitative analysis was initially directed by the following preliminary research questions: 1) How does exercise mode affect the muscle damage response? 2) What outcome measures are used in the investigation of EIMD? The muscle damage protocols identified in the literature have been summarised and several key themes identified around indirect markers of muscle damage. The identified themes were force loss (1), muscle soreness (2), CK (3), ROM (4), functional outcomes (5) and self-reported perceived recovery / readiness (6); the results related to each theme have been presented in Appendices A-F.

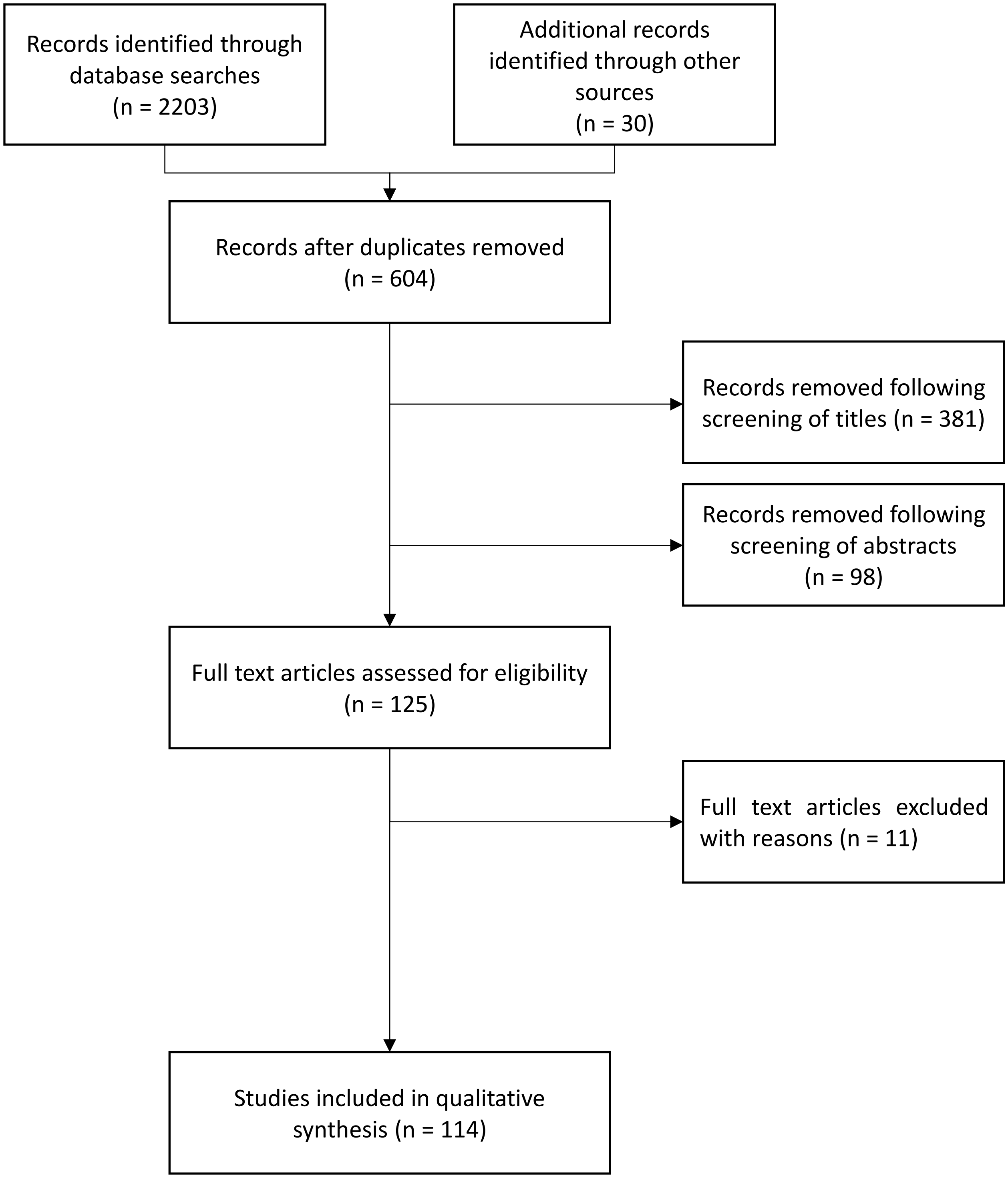

Figure 1-1. Literature search strategy to identify contemporary research between 1st January 2008 and 31st July 2020.

1.4 Muscle Damage Protocols

There have been a variety of protocols used to investigate the muscle damage response following exercise. The majority of research has used laboratory-based protocols to induce muscle damage, comprised of isolated eccentric actions or large multi joint/muscle eccentrically biased exercises. Isolated eccentric protocols have been primarily conducted using muscle actions at the elbow (25, 35-51) or knee (52-74); a limited number of studies have used actions of the forearm flexors (75), calf (76, 77) or shoulder (78). These isolated muscle group protocols are used as they have been extensively shown to result in muscle damage. However, the observed recovery responses following these isolated muscle group protocols may lack ecological validity. Large multi joint/muscle protocols have been conducted using squats (79-81), plyometric jumps (82-90), DR/walking (91-94) and cycling (62, 95). These compound exercises better represent sport and exercise conducted in day-to-day life, though do not truly reflect real-world activities. The exercises are often biased towards the eccentric phase of muscle action (e.g., down phase of squat under heavy load) which is associated with causing muscle damage (79-81, 96).

In recent years researchers have begun to consider the muscle damage response following activities which are representative of real-world sport and exercise settings. This provides greater insight into the potential muscle damage sustained in sporting environments, which is of great interest to facilitate the selection of optimal recovery strategies. A number of studies have examined the muscle damage response following repeated sprinting (15, 16, 27, 97-101). However, the sprints involve a rapid deceleration phase which causes the muscles to be loaded eccentrically, which may not truly reflect real-world sprinting activities. Muscle damage has been investigated following simulated game/sport protocols (basketball (28, 102), rugby (103), kayaking (104), dance (15, 27)) and intermittent exercise (Loughborough intermittent shuttle test (105) & high-intensity interval training (101)) aimed at replicating the physical demands of sporting environments. A limited number of studies have investigated muscle damage following real-world sporting events (football (106), rugby (107), marathon (108), half Ironman (109, 110)). These “real-world” investigations have been primarily focused on the muscle damage response in a competitive sport context. Research has not considered muscle damage following common exercise activities (e.g., exercise class (EC)) conducted by adults regularly in day-to-day life. Research is required to understand the muscle damage response following conventional day-to-day exercise activities. This insight would provide greater understanding into the recovery needs of individuals following common exercise activities. If exercise results in muscle damage or its symptoms (i.e., muscle soreness), this may affect adherence to subsequent exercise and present a barrier to exercise. In modern society there is a need to increase adult participation in regular exercise, insight into potential barriers due to muscle damage following common exercise activities may aid this process.

1.5 Markers of Muscle Damage

1.5.1. Force Loss

A decline in the ability of the muscles to generate force is considered the "gold standard" indirect assessment of EIMD (3, 4). Clustering individuals based on reduction in force generating capacity was shown to greatly increase the accuracy in predicting other indirect assessments of muscle damage (Creatine Kinase (CK) muscle soreness, ROM), supporting that force loss is the main indirect indicator of EIMD (39). Due to this force loss has been used extensively within the literature to identify and quantify muscle damage following exercise. Force loss has been assessed using a range of both isometric (Appendix A) (16, 25, 27, 35-38, 40, 42-48, 51, 54-57, 59, 64, 69, 71-73, 75, 78, 79, 82, 85, 88, 93, 96, 98-100, 105, 110) and isokinetic measures (25, 27, 35, 36, 39, 42, 44, 49, 52, 61, 64, 69, 70, 80, 83, 84, 88, 89, 92, 97, 103). The assessments used to quantify force loss vary within the literature, using both measures of force/torque and the rate at which these can be generated. The accurate assessment of these measurements requires the use of an isokinetic dynamometer. This equipment is extremely expensive, not portable and only accessible in universities and hospitals. Therefore, force outcomes requiring the use of an isokinetic dynamometer are not practical for assessing individuals following "real world" sport and exercise activities. There is a need for portable affordable equipment or proxy indicators which can be more readily attained to indirectly assess EIMD.

The magnitude of the force decline is dependent on the mode, intensity and novelty of the exercise stimulus (3). Concentric exercise results in a force reduction of 10-30%

immediately post exercise, however, this recovers within hours post exercise and likely represents neural and/or metabolic fatigue (4). Following eccentric exercise this decline is prolonged, indicating muscle damage has occurred (4). More recently, eccentric exercise has been shown to impair force production and action potential propagation to a greater extent, compared to similar concentric exercise (44). Additionally, eccentric exercise has been shown to result in a greater impairment in motor control compared to concentric exercise, even when both modes result in a similar overall isometric strength decline (75).

A large amount of the muscle damage research has investigated force loss following laboratory based eccentric exercise of isolated muscle groups (e.g., forearm flexors/knee extensors). Isolated eccentric exercise results in a significant decline in force generating capacity immediately post exercise (25, 36-38, 47, 49, 51, 54, 55, 65, 69, 70, 74), which remains for 72-96 h (43, 55, 70) before returning to pre-exercise levels. Several studies have observed declines in force generating capacity still evident 96-168 h post exercise (25, 36-38, 40, 42, 49, 52, 54, 59, 65, 74, 78). This suggests isolated eccentric exercise protocols result in significant force loss lasting at least 3-4 days. When the muscle damage response is more severe the recovery of force production can take 7+ days (57, 72, 78, 88).

Faster velocity contractions have been shown to result in a greater reduction in isometric force, with the affect much greater when the volume of contractions is increased (36). Highlighting how both the velocity and volume of exercise combine to affect the magnitude of muscle damage caused. When the muscle damage is performed over a greater range of motion there is a significantly greater reduction in isometric contraction force, resulting in a slower recovery towards pre-exercise ability (40). When the elbow and knee muscles were compared in response to muscle damaging exercise, a greater reduction in torque was observed in the arm muscles (25). Highlighting how smaller muscle groups may be more susceptible to muscle damage. However, these studies utilising eccentric exercise of isolated muscle groups are often completed using artificial contractions on an isokinetic dynamometer. Caution should be taken when considering how these findings may accurately reflect the “real world” strain placed upon the muscles when exercising in a natural environment.

Large multi muscle and/or joint laboratory-based exercise protocols have been shown to result in a decline in force generating ability. Plyometric jumping protocols using drop-jump (82, 84, 88) or vertical jump (83, 86, 89) exercises have been shown to significantly impair force production. Drop-jumps were shown to result in a decline in force production immediately post exercise, which remained significantly impaired for up to 7 days post exercise (84); a more extreme protocol completed with untrained individuals resulted in significant impairments up to 14 days post exercise (88). Conversely, when accentuated eccentrically loaded drop-jumps were used with resistance trained males, a small to trivial reduction in force generating ability was observed. Therefore, the training status of participants may explain the observed difference in force responses following drop-jump exercise. Vertical jumping exercise protocols have resulted in significant force declines 48h post exercise (83, 86), with a return towards pre-exercise capability over 4-7 days (83, 86, 89). The measurement time points were not consistent (i.e., every 24 h) across studies, making it difficult to determine the exact time-course of the force response following vertical jumping exercise; future research should ensure regular and consistent assessment time points are used.

Squatting exercises have been shown to result in a significant decline in force production immediately post exercise, which remains until 48-96 h post exercise with recovery occurring within 3-7 days (79-81). Variation in the type of squat exercise used may explain the observed differences in force loss and recovery. Eccentric and concentric cycling resulted in immediate declines in force production, however, a significant decline only remained at 24-48 h in the eccentric protocol; the pattern of force recovery is unclear as no further measurement time points were included (95). DR has been shown to result in a significant reduction in force generation for 24-48 h post exercise (91, 94, 111). Rate of torque development remained significantly impaired 72 h post DR when maximal torque was no longer impaired (111). This suggests DR may have a greater effect on the ability to generate force rapidly compared to the overall maximum force the muscles can produce. Similarly, downhill walking has been shown to impair force production significantly up to 72 h post exercise; no further measurement time-points were assessed (93). It is evident there is a need for research to include more consistent timings of force measurement, over a sufficient period, to ensure a clear picture of the force recovery time-course is provided.

Force loss has been assessed following several modes of exercise looking to replicate the demands of day-to-day sporting environments. Repeated sprints have been shown to impair force production significantly until 48-72 h post exercise (15, 16, 27, 97, 99). A simulated rugby match protocol was shown to significantly impaired force production for 24-48 h post exercise (103). Completing the Loughborough Intermittent

Shuttle Test which replicates the physical demands of football, resulted in immediate reductions in force generation which were still evident 24 h post exercise (105). This suggests the movements conducted in team sports may result in an impairment of the muscles to generate force over the subsequent 24-48 h. Completing a simulated dance protocol representative of the strains of contemporary dance, resulted in a significant impairment in force production which remained up to 24 h post exercise (15, 27). When the sprinting and dance activities were compared, the sprinting activity resulted in a more prolonged period of force impairment (15). This may highlight how the rapid eccentric deceleration following repeated sprints causes muscle damage which impairs the production of force. Currently it appears no research has investigated force loss following real world sporting events. This is likely due to the difficulty to directly assess force characteristics outside of laboratory settings and retest participants at repeated time points following the completion of the events.

In summary it is apparent that force loss is included extensively within recent muscle damage literature. Isolated eccentric exercise of small muscle groups has been shown to extensively impair muscle damage for at least 3-4 days post exercise. Large compound exercises completed in laboratory environments have also been shown to result in significant losses in force, with the time-course of recovery varying dependant on the exercise mode and participant type. Less research has considered the force loss response following simulated “real-world” exercise with the majority of this research using repeated sprinting protocols. Repeated sprinting appears to impair force loss similar to the response observed following laboratory based large compound exercises (i.e., squatting, jumping). Comparatively, following simulated team sport and exercise protocols, force loss appears impaired to a lesser extent. The lack of research assessing force loss following actual sporting events highlights a potential gap in the literature and may indicate the difficulty with assessing force loss in field-based settings. Research is required to determine how force loss may occur under these “real world” settings and how proxy indicators may be used for force loss, to enable muscle damage to be quantified more easily outside of laboratory environments.

1.5.2. Muscle Soreness

The assessment of muscle soreness provides another indirect indicator of muscle damage which has been extensively included within the literature (14-16, 25, 27, 28, 35, 36, 38-47, 52-54, 56, 57, 59, 60, 62-65, 67-70, 76, 79, 80, 82-89, 91, 93, 99-101, 103, 105, 107, 112). This has been primarily conducted by individuals rating their perceived soreness on a visual analogue scale (VAS) (Appendix B). The rating of soreness/pain has been assessed during passive movement, while completing a specific movement/type of exercise or as the muscle belly is palpated. Therefore, muscle soreness provides an indirect marker of muscle damage, which can be assessed quickly and easily, without the requirement for complex and expensive equipment.

Following isolated muscle damage of the elbow flexors and knee extensors, peak muscle soreness is observed 24-48 h post exercise (25, 35, 36, 38-42, 44-46, 52, 54, 57, 59, 60, 65, 68, 69). Muscle soreness then returns towards pre-exercise values, with this response more delayed when a greater magnitude of muscle damage has occurred (36). When the damaging exercise is completed at a higher intensity, the magnitude of soreness response is increased (41). When the same exercise is completed both eccentrically and concentrically, muscle soreness is reduced and peaks sooner, following the concentric protocol (44). When completed at the same relative intensity, isoload exercise causes more soreness compared to isokinetic exercise. It is suggested this is due to differences in the velocity and torque characteristics between the movements, key factors associated with causing muscle damage (52). Muscle fibre type has been associated with the soreness response following muscle damaging exercise, with type 2 fibres correlated with the muscle soreness 48 h post exercise (60). This suggests individuals who experience greater post exercise muscle soreness are more likely to have higher anaerobic performance capabilities and possess a greater percentage of type 2 muscle fibres. Individuals who are classified as high responders to muscle damaging exercise, have been shown to have greater muscle soreness following muscle damaging exercise (39).

When laboratory based full-body compound exercises are used, muscle soreness appears to occur quicker than with isolated muscle group exercises and the degree of soreness is less severe. Plyometric jumping muscle damage protocols have been shown to cause significant increases in muscle soreness, peaking between 24-72 h post exercise (14, 82-89). Muscle soreness was shown to increase and peak similarly following split squat muscle damaging exercise, at 48 h (79). Following downhill walking or running, muscle soreness appears to peak 48 h post exercise (91, 93). The observed muscle soreness peak at 48 h post exercise in some studies may be due to no measurement being obtained at 24 h (76, 86, 89, 91). Future research should ensure soreness is assessed at consistent time points to provide a better understanding of the time-course of the soreness response.

Repeated sprint muscle damaging exercise has been shown to increase soreness significantly and peak 48 h post exercise (16, 99, 100) When high intensity running protocols were investigated, only the repeated sprint protocol was associated with causing significant increases in muscle soreness (101). Highlighting how the eccentric phase of the deceleration from the repeated sprinting is responsible for the observed increases in muscle soreness. Soreness from the repeated sprinting has been shown to be greater in the quadriceps compared to the hamstring muscles (16). When female dancers completed either repeated sprints or dance specific muscle damaging exercise, soreness peaked 24 h post exercise (15, 27). The soreness response was slightly greater following the dance activity compared to the repeated sprinting. Following protocols used to simulate the demands of basketball and football, muscle soreness was shown to significantly increase and peak 24 h post exercise (28, 105).

There has been limited research which has assessed muscle soreness in response to real world sporting events. Following elite level rugby matches muscle soreness was shown to be increased up to 36 h post exercise (107). Muscle soreness was assessed following a half-ironman, however, no pre-exercise measure was obtained to identify if an increase had occurred (108). Currently, it appears no research has investigated the muscle soreness response following conventional exercise activities completed in day-to-day life. Research is required to assess muscle soreness consistently before and after sport/exercise events to understand the time-course of the muscle soreness response.

In summary it is apparent muscle soreness has been included extensively in recent muscle damage literature due to the ease at which it can be assessed. Muscle soreness has shown to increase significantly in response to both laboratory and field-based exercise. Following exercise simulating the demands of sport/exercise, muscle soreness may recover faster due to less muscle damage occurring, in line with that previously discussed for force loss. Less is known about how muscle soreness responds following "real world" sport/exercise activities. Muscle soreness may be a more applicable tool to be used in environments such as gym and leisure facilities to determine if activities are causing muscle damage.

1.5.3. Myofibrillar Proteins

Following muscle damaging exercise, the appearance of myofibrillar proteins within the blood has been investigated within the literature. The most widely investigated myofibrillar protein is CK (Appendix C). Along with CK, Myoglobin (Mb) and Lactate Dehydrogenase (LDH) have also been assessed in a number of studies. Myofibrillar proteins are assessed by analysing the concentration in the circulating blood, obtained using a venous blood sample.

There has been extensive research into the response of CK following isolated muscle damaging exercise of the elbow flexors and knee extensors (25, 35, 36, 38, 39, 41, 44, 45, 52-57, 60, 61, 64, 67-70, 113). Following exercise involving isolated eccentric muscle actions CK has been shown to increase significantly and peak at 24 (60, 61, 67, 70), 48 (41, 64), 72 (25, 36, 38, 41, 68, 69) and 96 (25, 35, 39, 41, 52, 54, 55) h post exercise. The peak increase in CK following isolated eccentric muscle damaging protocols, has even been shown to occur after 96 h post exercise (39, 45, 57). Isolated exercise of the elbow flexors and extensors causes a greater increase in CK compared to the knee extensors and flexors (25). When fast and slow muscle contractions were compared, only when a greater volume of contractions were completed (30 vs 210), was CK shown to be greater following the faster contractions (36). At the same relative intensity, isoload exercise caused a greater response in CK compared to isokinetic exercise (52). High responders to muscle damage display a significantly greater CK response compared to low responders; the inter group variation in the response is much greater in the high responding group (39). This highlights a limiting factor to assessing EIMD using CK, as the individual response is highly variable.

The CK response has been investigated following laboratory based full body exercise protocols to induce muscle damage. Following drop jumps CK has been shown to increase and peak 24 h post exercise (82, 84, 85, 87). The increase in CK following drop jump exercise appears relatively small in comparison to that seen following isolated eccentric muscle damage protocols. Completing twice the number of drop jumps (100 vs 50) was shown to cause a much greater increase in CK, 72 h post exercise (88). When vertical jumps were used to cause muscle damage, CK increased and peaked later, 72 h post exercise (90). Compared to the vertical jumps, an endurance cycling protocol produced a smaller CK response, with the peak increase observed 24 h post exercise (90). CK was shown to increase and peak 24-48 h post DR and walking (93, 94, 114). CK was only measured at 48 h in one DR study, therefore, this may not be when the peak increase occurred (94). Future work should measure CK at additional time points, to provide better insight into the CK time-course response following DR.

A number of studies have investigated myofibrillar protein responses following repeated sprint activities (16, 99-101). CK has been shown to significantly increase and peak 24 h post sprinting and remaining significantly elevated for up to 72 h (16, 99, 100). Following the Loughborough Intermittent Shuttle Test (LIST) CK activity peaked as with sprinting, 24 h post exercise. However, compared to sprinting the CK response returned to pre-exercise concentrations more rapidly 72 h post exercise. When comparing different high intensity interval running conditions, only 4 minute straight line runs and repeated sprinting resulted in significantly increased CK post exercise (101). The increase was greater following the repeated sprint protocol, likely due to the eccentric actions required during the deceleration phase of each sprint causing increased muscle damage.

Simulated match protocols were used to replicate basketball and rugby game settings, following these CK was shown to increase significantly, the peak increase occurring 24 h post exercise (28, 102, 103). In comparison, following elite level rugby matches, CK was shown to increase and peak 12 h post-match and remain significantly elevated after 36 h (107). CK increased to a greater extent and recovered slower from the elite rugby match compared to the simulated training session, likely due to additional muscle damage caused through collisions (103, 107). Therefore, research investigating sport or exercise involving contusion injury should consider how this may affect the CK response, which may alter the recovery time-course following exercise. Following a football match CK and Mb increased significantly, however, no other time points were measured, so the time-course of the recovery response is unclear (106). When measured immediately post a half-ironman, CK was significantly increased from pre event (110). CK was only assessed at one time point following the half-ironman, future research should ensure additional assessment time points are included, to provide greater insight into the recovery time-course of myofibrillar proteins following sporting events.

In summary myofibrillar proteins have been widely included in muscle damage research, with CK the protein most frequently assessed. CK has been shown to increase significantly following exercise which causes muscle damage, both in laboratory and “real world” settings. The response of CK may be more varied compared to other common indirect markers of muscle damage, with high responders to muscle damage displaying a much greater response. Additionally, the assessment of myofibrillar proteins requires the obtainment and laboratory analysis of venous blood samples. This procedure is invasive and the analysis of blood samples requires time and incurs costs for consumables and complicated laboratory analysis. Therefore, the analysis of myofibrillar proteins does not appear appropriate or accessible, to regularly monitor muscle damage in “real world” sport and exercise settings.

1.5.4. Range of Movement

A number of studies have considered how ROM may be affected following muscle damaging exercise (Appendix D). ROM is assessed by considering the arc a joint can operate over near the site of muscle damage. ROM is affected by the properties of the skin, subcutaneous tissue, tendon, articular capsule, bone and muscle (13). ROM assessments have been completed by measuring relaxed elbow joint angles (45, 47), the difference between maximal voluntary flexion and extension angles (25, 36, 37, 39, 40, 42, 70) or by the angle of voluntary knee extension (16, 115).

ROM has been shown to be impaired greatest immediately following (36, 37, 39, 70), 24 h (16, 25, 40, 47, 115), 36 h (45) and 48 h post (39, 42, 47) muscle damaging exercise. When isolated eccentric exercise was completed using the elbow flexors and knee extensors, the impairment in ROM was more severe in the elbow flexors (25). This may highlight how muscle damaging exercise of smaller isolated muscle groups, impairs ROM to a greater degree. Following muscle damaging exercise ROM has been shown to be impaired in both the ipsilateral and contralateral arms (47). Therefore, it appears it is not just the exercising limb which has impaired ROM following muscle damaging exercise. When eccentric elbow flexor exercise was compared over different ROM's, the larger ROM exercise resulted in a greater impairment of ROM, which peaked 48 h after the smaller ROM exercise (40). Completing a high volume of faster eccentric actions of the elbow flexors resulted in a greater reduction in ROM (36). When the number of muscle contractions reduced, there was no difference in ROM between the fast or slow contraction groups. Low responders to muscle damage have been shown to have less impaired ROM compared to medium and high responders (39). Additionally, the time-course of the response is different for the low responders, with the peak reduction in ROM occurring sooner than observed for the medium and high responders.

The majority of the literature has considered how ROM is affected following isolated eccentric lab-based exercise, only three studies have considered it following other modes of exercise (repeated sprints and eccentric cycling) (16, 62, 115). Completing repeated sprints which result in muscle damage impaired ROM measured at the knee for up to 48 h post exercise (16). A second study which investigated ROM following repeated sprints found ROM to still be impaired 72 h post exercise (115). After completing muscle damaging eccentric cycling ROM was shown to be impaired in the knee extensors and flexors (62). Together these results suggest that larger multiple muscle and/or joint exercise protocols which cause muscle damage result in reduced ROM in the days immediately post exercise. Further research is required to provide more insight into how ROM may be impaired following conventional muscle damaging exercise involving large compound exercise (e.g., DR, drop jumps, squats). This insight would provide more understanding into how conventional sport and exercise activities may result in reduced ROM.

In summary ROM has been shown to be impaired following a variety of muscle damaging exercise modes, providing an indicator of muscle damage. ROM has been predominately investigated following isolated eccentric exercise laboratory protocols, with the peak impairment in ROM occurring within 48 h post exercise. Less research has investigated how ROM is impaired following muscle damaging exercise involving large compound exercises across multiple joints and/or muscles. Research is required to provide greater insight into how ROM may be impaired following larger compound modes of muscle damaging exercise, representative of those completed in day-to-day sport and exercise settings.

1.5.5. Functional Performance

In recent years there has been a shift in the literature to investigate functional outcome measures following muscle damaging exercise (Appendix E). These measures may provide information which has greater real-world applicability in sport and exercise settings and can be more readily obtained outside of laboratory environments.

Table 1-1. Jump assessments included in exercise-induced muscle damage research.

Jump Type	Definition
Countermovement Jump	Jump involving an initial downward phase (countermovement) followed by an upward phase pushing off from the toes (116).
Squat Jump	Jump begins from stationary semi-squatted position with the athlete immediately pushing up and off the toes (116).
Drop Jump	An initial drop phase stepping from a height (i.e., 30cm step) and subsequent rebound phase, pushing up off the toes rapidly to jump up and limit the ground contact time (117).

The most included functional assessment has been the measurement of vertical jumping. Jumping performance (Table 1-1) has been assessed in the muscle damage literature using countermovement jumps (CMJ), squat jumps (SJ) and drop jumps (DJ). CMJ performance has been shown to be impaired following repeated sprint (15, 16, 27, 101, 115), dance (15, 27), DJ (82, 87) cycling (62) and simulated team sport (28, 102, 103) exercise which causes muscle damage. CMJ capability appears most impaired immediately post exercise, as evidenced by a 5-17% immediate reduction in performance

(15, 27, 82, 87, 101, 103, 118). The immediate reduction in jump performance appears similar to the reductions observed in force loss immediately post exercise due to fatigue (discussed in 1.5.1). CMJ has been shown to remain impaired for 24-48 h following muscle damaging exercise before it returns towards pre-exercise levels (15, 16, 27, 28, 82, 87, 101-103, 105). Following eccentric cycling CMJ ability was shown to be impaired to lesser extent (62) Eccentric cycling utilises different muscle actions and may explain why this exercise may impair CMJ ability less. Conversely, intermittent running protocols were shown to not impair CMJ performance (101). The running protocols do not appear to have caused muscle damage, as assessed by changes in CK/muscle soreness, which would likely explain why no impairment in CMJ was observed (101). SJ performance has been investigated less with the majority of research including CMJ assessments. When included, SJ performance appears impaired on a similar time-course to CMJ performance (82, 87). This impairment remains for 24-48 h post exercise and then returns towards pre-exercise levels. As observed for CMJ performance, SJ ability may be impaired to a lesser extent after eccentric cycling (62).

In recent research the assessment of RS has also been included following dance and sprint muscle damaging exercise (15, 27). RS considers an individual’s stretch-shortening cycle ability and is vital for producing a large amount of force in a short time, beneficial for many sport and exercise settings (119). RS was impaired immediately post muscle damaging exercise and remained impaired at 24-48 h before returning towards pre-exercise levels. The time-course of the impairment and recovery of RS appears similar to that observed for CMJ/SJ performance following muscle damage exercise.

Sprint performance provides another functional assessment which has become of interest in the muscle damage literature in recent years. Sprint performance has been shown to be reduced by 2-16%, 24-48 h post exercise, before returning towards pre-exercise levels following sprinting, jumping and simulated basketball exercise protocols (14, 16, 28, 83, 115). The time course and recovery of sprint performance following EIMD appears similar to that observed for measures of force loss (16, 83, 115).

Agility is another functional component vital for performance in many exercise and sport settings (20). Recent research has included the assessment of agility following plyometric jumping and sprinting muscle damaging exercise protocols (14, 16, 83). Agility was shown to be significantly impaired (7-17%) following muscle damaging exercise, with peak impairment occurring 24-48 h post exercise. Following repeated DJs which caused muscle damage, agility remained significantly impaired up to 72 h post exercise (14). Therefore, agility appears to provide another functional assessment which is impaired following exercise which results in muscle damage.

The assessment of balance ability has been included in recent research using repeated sprint and split squat exercise protocols. Balance ability is associated with performance and the incidence of injury in sport (120, 121). Balance has been assessed during static and dynamic conditions (16, 81). The effect of these muscle damaging exercise modes on balance ability appears equivocal. Following repeated sprints both static (42%) and dynamic (9%) balance were significantly impaired (16). In contrast, following split squats there was no significant impairment in balance ability (81). Both exercise protocols resulted in significant muscle damage, as evidenced by a reduction in force generating capacity. Therefore, it may be expected that balance ability would also be impaired following the split squat exercise. It was suggested that visual and vestibular systems may not be affected directly by muscle fatigue and explain why no reduction in balance ability was seen (81). Though balance was not significantly reduced a trend towards a reduction was evident. However, if this was the mechanism responsible for the maintenance of balance, it would be expected this would be seen across both studies (16, 81). More research is required to further investigate if balance is affected following additional modes of muscle damaging exercise and how this relates to common assessments for muscle damage.

The functional assessments which have been monitored in response to muscle damaging exercise have predominantly involved lower limb tests. This is likely due to the exercise protocols used to induce muscle damage primarily involving the legs, therefore, impairments would be expected to be present on assessments involving their use. However, one study did incorporate a repeated push-up assessment, which would assess upper body function following muscle damaging exercise. Following rugby matches a small to moderate impairment was observed in the repeated push-up ability, 12-36 h post exercise (107). Collisions during the rugby matches may have contributed to muscle damage and subsequent reduced repeated push-up ability; further research is required to determine if the observed reductions are present without contusion injury.

Interestingly, the impairment and recovery of functional assessments, (CMJ/SJ, RS, agility, balance & sprint ability) appears to respond on a similar time-course to that of measures of force generating capacity (15, 16, 27, 81-83, 103, 105, 115). These functional assessments may therefore provide alternative indirect markers for muscle damage and be related to the mechanisms which result in force loss. However, force loss alone may not be the only mechanism responsible for the impairment in some of these functional measures. Tests used to assess agility have incorporated short bursts of sprinting combined with rapid changes in direction (14, 16, 83). When sprinting and agility have been considered in response to the same exercise activity, a greater reduction has been observed in agility (14, 16, 83). Therefore, force loss cannot be the only mechanism responsible for the observed changes in sprint performance and agility. Individuals who completed muscle damaging exercise were shown to have increased (+21%) ground contact time, during the turning manoeuvres of an agility test (83). It was suggested this is due to damaged muscle having a reduced tolerance to impact forces, during stretch-shortening cycle movements. This would reduce the ability to utilise ground impact forces, increasing contact time during the braking and push-off phases of turning manoeuvres. This would be supported by the greater impairments observed in CMJ compared to SJ performance, which requires more utilisation of the stretch-shortening cycle (16, 82). Further research is required to elucidate the mechanisms underpinning functional impairments following muscle damaging exercise. Surprisingly, it appears functional outcomes have not been considered following conventional modes (isolated eccentric contractions, DR) of exercise which have been used extensively over the last two decades to investigate EIMD.

In summary, in recent years research has started to investigate how functional outcomes, which are related to athletic performance and risk of injury in sport, may be affected in the presence of muscle damage. The time-course over which these functional outcomes (jump ability, balance, agility) are affected following muscle damaging exercise appears similar. These functional assessments provide accessible measures which may be used to readily monitor muscle damage and recovery outside of laboratory settings. Additionally, the assessments involve completing movements combing multiple muscles and/or joints which may enhance the ability to detect impairments due to EIMD. Further research is required to provide greater insight into how functional outcomes are affected following muscle damaging exercise and how they may provide proxy indicators for muscle damage.

1.5.6. Psychological

There has been very limited research which has considered how self-reported/perceived recovery may be affected by EIMD (63, 71, 78) (Appendix F). Recovery has been described as multilevel, comprising of physiological, psychological and social processes (24). Therefore, to take a holistic approach and completely consider how an individual is recovering from EIMD, both physical and psychological outcomes need to be monitored. Athletes are regularly monitored in elite sport using self-report measures (Profile of Mood States (POMS), Recovery-Stress Questionnaire for Athletes (RESTQ-sport), Rating of Perceived Exertion (RPE)) to monitor their perception of training load and ensure appropriate recovery is administered (122, 123). Understanding the response of self-reported psychological measures following muscle damaging exercise may have implications for the suitability and motivation of an individual to complete further exercise.

Individuals who rated their readiness following muscle damaging exercise felt significantly less (18%) ready to complete a maximal treadmill test and had a significantly shorter (-8%) time to exhaustion; readiness was only measured once immediately before exercise (63). Therefore, how an individual feels after muscle damaging exercise may affect how they are functionally able to undertake further exercise. Using a simple recovery scale ranging from 0 (very well recovered) to 10 (very poorly recovered), individuals reported feeling less recovered up to 72 h post muscle damaging exercise of the knee flexors; this effect was observed with both passive and active recovery (71). Perceived recovery was not assessed after 72 h so it is unknown by what time recovery to pre-exercise scores would have occurred. Following isolated muscle damaging exercise of the shoulders, perceived recovery was significantly impaired up to 72 h post exercise before returning towards pre-exercise values by 168 h (78). Together, these studies suggest that EIMD may reduce readiness to complete further exercise. More research is required to provide greater insight into how self-reported psychological outcomes are affected following muscle damaging exercise.

All of the studies investigating psychological recovery were conducted using muscle damaging exercise of isolated muscle groups (63, 71, 78). These activities are quite extreme and as highlighted already (section 1.5.1) result in greater muscle damage as evidenced by increased force loss. Research is needed to determine how psychological recovery is affected following large multi muscle/joint muscle damaging exercise. These activities are more representative of those commonly undertaken in sport and exercise settings and understanding how psychological recovery responds following these activities would have more practical implications.

The research conducted so far into psychological recovery following EIMD has all been completed by getting individuals to rate recovery on simple Likert scales (63, 71, 78). As discussed, self-report measures are commonly used in elite sport and are comprised of more complex assessments such as the POMS and RESTQ-Sport. Research is required employing more in-depth assessments of psychological recovery, to provide additional insight into how an individual's perception of readiness to exercise/recovery is affected by EIMD. Psychological recovery should be assessed at additional time points, to provide clear insight into the recovery time-course of these outcomes following muscle damaging exercise.

In summary, there has been limited research using simple assessments investigating how psychological recovery may be affected by EIMD. Self-report measures are commonly used to monitor recovery in elite sport and may provide vital insight in considering how ready an individual is to complete further exercise following muscle damaging exercise. Further research is required using more in-depth assessments and following modes of exercise more representative of those undertaken in day-to-day sport and exercise settings.

1.6 Factors Affecting the Muscle Damage Response

1.6.1. Repeated Bout Effect

There has been considerable research investigating how repeating a bout of exercise may affect the subsequent muscle damage response. The consensus within the literature is that after completing a second bout of muscle damaging exercise, the response is dampened due to a protective adaptation conferred from the initial bout of activity (3-5). As discussed, (section 1.1) this concept has become widely known as the RBE. In recent years research has looked to provide further insight into how the timing, intensity and type of exercise affect the protective effect conferred from previous exercise.

The RBE has been evidenced on common indirect markers of muscle damage (force loss (27, 38, 47, 49, 56, 65, 70, 76, 85, 97, 105, 115), muscle soreness (38, 47, 49, 56, 65, 76, 93, 97), myofibrillar proteins (38, 56, 97, 114, 115) and ROM (47, 70)) across varying modes of exercise. Research to determine if the RBE may be evident on functional outcomes has so far been equivocal. CMJ, RS, agility and sprint performance have been shown to be impaired following a subsequent bout of dance or repeated sprint activities, suggesting the previous bout of exercise did not mitigate the response (27, 105, 115). The individuals who completed activities were accustomed to the type of exercise, which may explain why no RBE was evident on these performance outcomes. Interestingly, after repeated sprinting the RBE was still evident on standard markers of muscle damage (force loss, muscle soreness, CK) even though no effect was evident for functional outcomes (115). It was suggested this highlights how conventional indirect markers of muscle damage may not accurately predict changes in functional movement outcomes; research is required to further investigate these relationships. Conversely, following DJ exercise, a RBE was evident on functional outcomes (CMJ and SJ) following a second bout of exercise (82). When the RBE was observed following the DJs, the resistance trained participants were unaccustomed to the muscle damaging activity, which may explain why a protective effect was conferred on functional outcomes, from the initial bout of activity (82). Further research is required to elucidate how the RBE may be evident for functional outcomes, dependant on the mode of exercise employed and how accustomed individuals are to the muscle damaging activity.

Research in recent years has sought to further investigate factors which may affect the RBE. Isometric exercise of the knee extensors completed two weeks prior to a subsequent bout of exercise, was shown to reduce the magnitude of the muscle damage response (70). Completing isometric preconditioning exercise with untrained men attenuated the muscle damage response following eccentric exercise of the elbow flexors; the protection conferred was similar for both fast and slow exercise (49). The RBE has been shown to transfer and provide protection to the contralateral previously non-exercised limb (47). The protection offered by the initial exercise bout may be greater in the ipsilateral arm, as evidenced by comparatively less strength losses compared to the contralateral group. Low intensity eccentric contractions completed before maximal eccentric muscle damaging exercise, have been shown to attenuate the muscle damage response in the contralateral arm (38). The magnitude of protection was diminished as time between the exercise bouts increased up to three weeks post exercise. Therefore, the RBE appears to offer protection against a subsequent bout of activity, however, this protection may be greater in the previously exercised arm and may diminish more rapidly when the initial exercise bout is low intensity. Similarly, a contralateral RBE was evident when repeating exercise after 6 weeks in the legs; surprisingly this was not affected by leg dominance as had been expected (56). An initial lower volume (30) of DJs was shown to provide protection against a second higher volume (50) bout of exercise, resulting in a reduced muscle damage response (82). When the duration of DR was increased gradually over four exercise visits, the muscle damage response was attenuated compared to the group which completed one constant 40 min exercise bout; similar strength gains were evident for both groups (93). This suggests a gradual build-up of the exercise stressor provides a RBE, avoiding muscle damage and still providing comparable strength gains to constant exercise.

In summary, completing a bout of muscle damaging exercise is known to confer a protective effect against subsequent similar exercise activities, commonly termed the RBE. The RBE has been extensively observed on common indirect indicators of muscle damage (force loss, muscle soreness, CK). Recent research has sought to investigate if the RBE is evident on functional performance outcomes. Further research is required to provide greater insight into how the RBE may occur for functional outcomes and how these relate to the responses observed in common indirect markers of muscle damage.

1.6.2. Training Status

There has been limited research into how training status may influence the muscle damage response following exercise. Only two studies have directly compared the muscle damage response between individuals classified as trained and untrained. Long distance runners, cyclists and untrained individuals were compared following muscle damaging exercise of the knee extensors (64). A greater reduction of force generating capacity was observed in the untrained group compared to the distance runners and cyclists, indicating that more muscle damage occurred. However, the responses observed for muscle soreness and myofibrillar proteins were similar between groups. Outcomes were assessed immediately post exercise and at 48 h, any difference between these times (i.e., 24 h) was not observed. Conversely, following muscle damaging squat exercise a similar response was observed in indirect markers of muscle damage for both the trained and untrained individuals (96). More research is required to provide clarity into how the muscle damage response is affected by training status and which outcome measures reflect this.

Currently, research has included conventional indicators of damage (force, muscle soreness, myofibrillar proteins), further work should consider outcomes which may be directly related to the physical demands of sport and exercise. Functional performance tests assess movement patterns and forces similar to those that are reflected during sporting activity. This provides practitioners with the ability to assess functional performance this outside of laboratory settings, using low tech and low-cost equipment and profile many individuals at regular intervals (21). Balance ability is associated with increased performance when completing athletic manoeuvres and a reduced risk of injury (120, 121). RS provides a functional outcome used to assess athletic ability, optimise training, reduce injury and monitor recovery (119). Therefore, using functional outcomes may be more ecologically valid for monitoring muscle damage and the influence of training status, in “real world” sport settings compared to conventional indirect markers (i.e., force loss, myofibrillar proteins).

A limitation in understanding how training status may influence the muscle damage response relates to how individuals have been classified as “untrained” (64, 96). In one study the untrained individuals were described as “physically active” and were able to produce comparable torque and work during exercise to their runner and cyclist counterparts (64). This may suggest they were not truly “untrained” as it would not be expected that they had the same exercise capacity as individuals who participate in exercise 5-7 times a week. In the second study, the untrained group had no resistance training experience, however, they were reported as being active in sport for two years and taking part in exercise at least 3 times a week (96). Therefore, the responses are likely to reflect differences between individuals who are and are not “resistance trained”. Research is required to investigate the muscle damage response between active individual and individuals who do not regularly complete any form of exercise. Understanding how “inactive” individuals may respond differently could provide vital insight into potential barriers to exercise and assist with informing individuals to increase motivation and adherence to exercise.

1.6.3. Sex

Previous reviews have discussed potential differences in the response to muscle damaging exercise between males and females (124, 125). Research in animal studies has shown that females receive a smaller increase in CK following strenuous exercise compared to males, due to greater circulating oestrogen levels (124). However, studies using eccentric exercise in humans have not found that females receive a different degree of muscle damage and the topic remains debated. It has been suggested that the inflammatory response following muscle damaging exercise may differ between males and females, however more research is required (124, 125).

Within the recent muscle damage literature only 15 of the reviewed studies included female participants, with the majority of research being conducted with male participants. Only three studies directly compared the responses between male and female participants after completing muscle damaging exercise. Following a resistance training protocol involving the elbow flexors, males exhibited greater responses in force loss and inflammation compared to females (46). The recovery of the indicators of muscle damage occurred over a similar time course for both sexes, with the exception of muscle soreness which was more delayed in the males. Conversely, following exercise of the knee extensors, indicators of muscle damage were similar between sexes except for CK, which exhibited a much greater response in the male group (54). The increase in CK observed in males remained when controlling for muscle mass surface area, suggesting increased muscle mass did not explain the greater response. It was suggested the lower CK change in females may be attributed to oestrogen increasing membrane stability, leading to less CK release into the circulation. Exercise induced pain was observed to be similar between both sexes after completing an eccentric strength exercise protocol in the arms (126).

Together these results suggest the debate remains and further research is required to definitively support the muscle damage response being different between males and females. Caution should be taken when assessing the CK response in female participants, as oestrogen seems to provide a protective effect, leading to a blunted CK response. Researchers should take caution when grouping male and female participants and ensure there is no difference in the response of outcomes between sex.

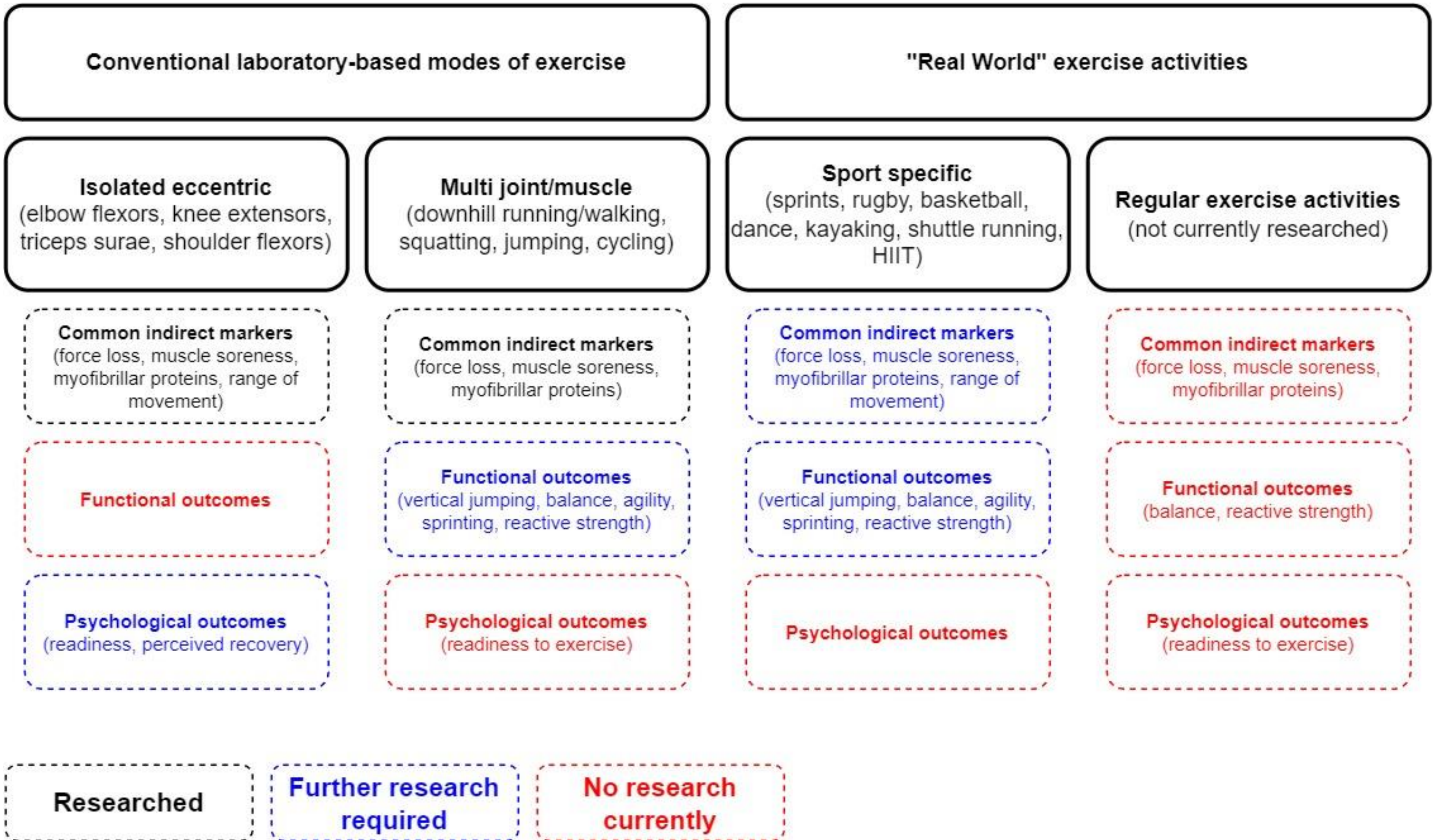

Figure 1-2. Modes of exercise and outcome measures used in the investigation of exercise-induced muscle damage.

1.7 Summary

1.7.1. Conclusion & Gaps in Literature

In recent years there has been a shift within the muscle damage literature to investigate muscle damage following activities representative of day-to-day sporting environments, outside of laboratory settings. Research has begun to include functional outcomes alongside traditional indicators of muscle damage, which are accessible and meaningful to individuals regularly taking part in sport and exercise. Investigations have begun to consider how psychological outcomes may be affected by EIMD, leading to a more holistic approach to monitoring recovery from muscle damaging exercise. Current research has focused heavily on paradigms which relate to competitive sport and there is a need to consider muscle damage following conventional exercise activities completed in daily life.

The following areas have been identified as key gaps in the literature in the synthesis of this review (Figure 1-1):

- Recent muscle damage research shifted away from using conventional eccentrically biased laboratory-based modes of exercise. This research has primarily focused on muscle damage in response to modes of exercise representative of those undertaken in competitive sport. Research is required to investigate the muscle damage response following common day-to-day exercise activities (i.e., fitness classes).
- Research is required to compare the muscle damage response from conventional “real world” exercise activities and widely used laboratory-based muscle damaging modes of exercise. This will highlight how the recovery needs following everyday

exercise may not reflect recovery from exercise activities completed in controlled environments aimed at causing muscle damage.

- There is a gap within the literature to understand how functional outcomes are affected by conventional laboratory modes of exercise (i.e., DR). Recent research has begun to include functional outcomes (i.e., balance/agility) along with conventional markers to monitor recovery from EIMD. However, this research has been conducted using sport specific modes of exercise. This would provide further insight into how functional outcomes are impaired following muscle damaging exercise.
- Limited research has considered how psychological recovery may be impaired following muscle damaging exercise. Further research is required to examine psychological recovery following muscle damaging exercise, incorporating more detailed psychological assessments. This insight may enhance the selection of recovery strategies and aid adherence to further sport and exercise.
- There is a need for research to compare how muscle damage occurs in individuals who do not take part in any structured exercise compared to individuals who are regularly active. Current research has included participants not accustomed to the muscle damaging activity used and individuals who regularly take part in other forms of physical activity, which are unlikely to reflect the responses in individuals who are extremely inactive.
- Research should take a more complete (holistic) approach to monitoring recovery from muscle damaging exercise. Investigations regularly include multiple indirect indicators of muscle damage which respond over a similar time-course. Recent investigations have included functional outcomes which also appear affected over the same time-course as the conventional indirect indicators. This approach can

be furthered to include self-reported psychological outcomes to create a complete view of recovery from exercise (physiological, functional & psychological). Understanding how these outcomes respond together may provide a more complete approach to monitoring recovery from EIMD and be more appropriate and accessible for all.

1.7.2. Research Questions

This thesis is set out to investigate the following questions:

1) Does conventional laboratory-based muscle damaging exercise affect functional outcomes?
2) Is self-reported psychological recovery affected by muscle damaging exercise?
3) Do common day-to-day exercise activities result in muscle damage?
    a. How does the response compare between more and less active individuals?
4) How does recovery compare between conventional laboratory-based muscle damaging exercise and regular exercise activities of daily life?

2. Materials and Methods

2.1 Introduction

All research presented in this thesis was conducted in accordance with the Declaration of Helsinki. Ethical consideration and comprehensive risk assessments were provided in all instances to the University of Essex Ethics Committee and approved prior to commencing experimental work. Participants were recruited through word of mouth and online via departmental social media (Facebook & Twitter), using recruitment notices which had received ethical approval. All participants were fully informed and provided written consent prior to commencing participation in the research.

All data collected and analysed within the experimental chapters of this thesis were numerical quantitative data. This thesis built on existing findings within the muscle damage literature, therefore, a number of measures were selected and employed in line with previous research. Several measures reoccur across the experimental chapters, due to their response being investigated across multiple environments and modes of exercise. The reoccurring measures will be outlined in the current chapter. Subsequent non-reoccurring measures will be introduced and outlined within the relevant chapter. Table 2-1 highlights the measures included within each experimental chapter.

Table 2-1. Measures included by experimental chapter

Measure	Experimental Chapter			
	3	4	5	6
Heart Rate	■	■	■	
Rating of Perceived Exertion	■	■		■
V̇O2peak	■	■		
Force Loss	■	■	■	
Muscle Soreness	■	■	■	■
Creatine Kinase		■	■	
Balance		■	■	
Reactive Strength		■	■	
Range of Movement		■		
Readiness to Exercise		■	■	■
Warwick Edinburgh Mental Well-being Scale (WEMWBS)				■
Rating of Fatigue				■

2.2 Reoccurring Measures

2.2.1. Force loss

As discussed previously (section 1.5.1) the measurement of force loss is widely considered the most valid and reliable “gold standard” indirect assessment of EIMD (2-4, 13). Research in recent years has continued to include the assessment of force loss as an indirect marker, to determine if muscle damage is present following several modes of exercise (15, 16, 38, 82, 88, 93, 105, 110). Force loss has been measured using a range of both isometric and isokinetic protocols. The measurement of isometric force is technically simple and has been shown to be associated with isokinetic measurements (127). Therefore, isometric force provides an assessment which can be measured quickly and consistently under laboratory conditions, offering benefits when testing over repeated time points in conjunction with other outcomes.

Knee extensor force (N) was measured (1000Hz) using maximal voluntary isometric contraction’s (MVIC), with a calibrated load cell dynamometer (Kin-Com dynamometer, Chattanooga Group Inc.; Hixon, TN, USA), attached around the participants right leg superior to the ankle malleoli, with a Velcro strap. Participants were seated upright, with the hip at 90° and knees at 80° flexion and instructed to remain seated with their arms across their chest; a securing strap was placed around the right thigh and waist to prevent movement during the contractions (128, 129). Three submaximal warmup contractions were completed each visit. Participants were requested to complete three MVICs lasting 3-s, with 60-s rest between contractions. Participants received a 3-s verbal countdown before extending their knee as “fast and as hard as possible” on each contraction; verbal encouragement was provided. Peak force (N) was calculated for each trial by taking the maximum value during the 3-s contraction. The peak force of the three MVIC trials was taken and used in analysis.

2.2.2. Muscle Soreness

It is well established (discussed in section 1.5.2) that muscle soreness increases following exercise which results in muscle damage (3, 4, 13). Muscle soreness has continued to be included as an indirect indicator of muscle damage in recent years, in research investigating varying modes of exercise (15, 16, 25, 82, 93, 105). The level of muscle soreness is commonly assessed using pain scales such as the VAS and numerical pain rating scale, due to the ease and short duration required to administer (130). The VAS comprises of a single continuous vertical or horizontal line, often 100 mm in length, anchored by two verbal descriptors for each extreme of pain (131). The measurement continuum of the VAS is said to provide greater sensitivity than a numerical scale (130). The VAS has been reported as a reliable assessment for musculoskeletal pain and is the most commonly used assessment for DOMS within muscle damage research (132, 133). Another method commonly used to assess DOMS is by applying pressure with an algometer to the muscle and assessing the point where the sensation of pressure becomes a sensation of pain, known as the pressure pain threshold (PPT). Pain assessed using the VAS and PPT has been shown not to correlate, suggesting these assessments may reflect different aspects of pain (134). The methodological challenges of standardising the site of PPT assessment and the apparent variability in the site of maximal tenderness influence the value of this approach (135, 136). The VAS has been suggested as the most appropriate method for use when using a single assessment to indicate the time-course of DOMS, with a standardised protocol (134).

A 100 mm visual analogue scale (VAS) comprising of a continuum from “no pain” to “the worst pain you can possibly imagine” was used to determine ratings of muscle soreness. Participants were required to mark their pain on the VAS and the distance was measured (to the closest mm) between the marked point and “no pain” to determine the muscle soreness score (137). Muscle soreness ratings were assessed during muscle contraction, to apply a stimulus to the muscle, as soreness is not felt while the muscle is still (134).

2.2.3. Creatine Kinase

As discussed (section 1.5.3), it is well documented that unaccustomed eccentric exercise leads to increased membrane permeability and the subsequent appearance of muscle proteins within the blood (2-4). Research has investigated the response of several muscle proteins (CK, Mb, troponin, myosin heavy chain) following muscle damaging exercise. The most investigated protein by far has been CK, likely due to the relatively large increase observed in the circulation following muscle damaging exercise and the moderate cost to conduct CK assays (3, 4). Creatine Kinase is a compact enzyme found in tissues where there is a high demand for energy (138). CK has three tissue-specific isoenzyme forms: CK-MB (cardiac), CK-MM (muscle) and CK-BB (brain) (139). CK-MM is usually confined to the muscle and its appearance in circulating serum concertation has been used to investigate muscle damage (2-4, 138). There has been large variation in the observed CK response depending on the mode of exercise employed and variability between individuals (high vs low responders) (3, 4, 138). Debate remains within the literature as to the suitability of CK for indicating and quantifying muscle damage. However, CK has continued to be included within the literature in recent years, as an indirect indicator for muscle damage following exercise (16, 28, 38, 39, 41, 53, 55, 67, 70, 93, 106, 107, 115).

CK levels were assessed using a 6 ml blood sample drawn by venepuncture from a forearm vein at the antecubital fossa; all samples were taken by the lead investigator trained in phlebotomy. Blood samples were collected in a sterile serum separator tubes (Vacutainer BD UK Ltd, Oxford, UK). Blood was centrifuged for twelve min at 1300 rpm to separate serum (Heraeus Labofuge 400R, Thermo Fisher Scientific, Massachusetts, USA). Serum samples were transferred into 1.8ml CryoPure tubes (Sarstedt AG & Co., Nümbrecht, Germany) and frozen at -80°C for further analysis. Assays were conducted by an external laboratory (CBAL, Cambridge, UK) to determine serum CK concentration.

2.2.4. Balance

Balance or postural control is a dynamic process involving continuous feedback from sensory inputs while executing neuromuscular actions, to maintain the body in a state of equilibrium (120, 121). Balance can be categorised into static and dynamic forms (121). Static balance is the ability to maintain a base of support with minimal movement. Dynamic balance is the ability to maintain or regain a stable posture while performing a task (121). Dynamic balance is critical for the completion of many athletic movements (16, 120, 121). Greater balance ability is associated with improved performance, whereas reduced balance is associated with an increased risk for injury (120, 121). Factors such as proprioceptive deficits, muscle weakness or injury and participating in sport/exercise are known to affect balance (16, 140). Less is known about how EIMD may impair balance (discussed in more detail in section 0), with limited research having been conducted in this area (16, 81).

The Star Excursion Balance Test (SEBT) is a valid and reliable measure of dynamic balance which has been used with both clinical and athletic populations (141). The SEBT eight reach directions make it lengthy to administer, while pressure applied to the ground during the assessment may limit the ability to apply the test accurately. This led to the development of the Y-balance test (YBT), a more simplified version of the SEBT, which is completed using a commercially available testing device (142). The YBT has been shown to be reliable for measuring dynamic balance while maintaining a single limb stance (143, 144).

Balance ability of the lower extremities was assessed using the YBT kit (Functional Movement Systems; USA), which consists of a stance platform connected to PVC pipes reaching out in the anterior, posteromedial and posterolateral directions (144) (Figure 2-1). The participant pushes a reach indicator along each of the pipes allowing for the precise measurement of each attempt; each pipe is marked in 5mm increments.

The YBT protocol was conducted as previously described within the literature (143, 144). Before commencing the test, each participant viewed a physical demonstration of how to perform the YBT from the investigator. As previously suggested, six practice trials were performed in each direction, on each leg, to avoid the influence of a learning effect (145). Participants completed the practice trials at each visit to the laboratory before the assessed portion of the YBT commenced. Following the instructional demonstration and practice trials, the test with measurements was completed. Participants stood on the centre stance platform with the most distal aspect on the foot immediately behind the start line. While maintaining a single leg stance, the participant pushed the reach indicator as far as possible, using the opposite free limb. This was conducted in the anterior (Figure 2-3), posteromedial (Figure 2-4) and posterolateral (Figure 2-5) reach directions, with both limbs. Three consecutive trials were completed for each direction and limbs were alternated to reduce fatigue. The specific testing order was right anterior, left anterior, right posteromedial, left posteromedial, right posterolateral and left posterolateral.

Reach distance was measured to the nearest 5mm in line with where the most distal part of the foot finished. The trial was discarded and repeated if the participant: 1) a unilateral stance on the platform was not maintained (e.g., touched the floor), 2) contact was not maintained with the reach indicator (e.g., kicked out), 3) the reach indicator was used for support (e.g., foot resting on top) or 4) failed to return to the starting point under control. The mean of the three trials in each direction was used for analysis (143). A composite reach score normalised to limb length was calculated for each limb using the equation: *Composite (%) = (Sum of three reach directions ÷ 3 x limb length) x 100*. Limb length was measured from the anterior superior iliac spine, to the inferior distal surface of the medial malleolus, while standing. A mean balance score was calculated using the composite scores from both limbs.

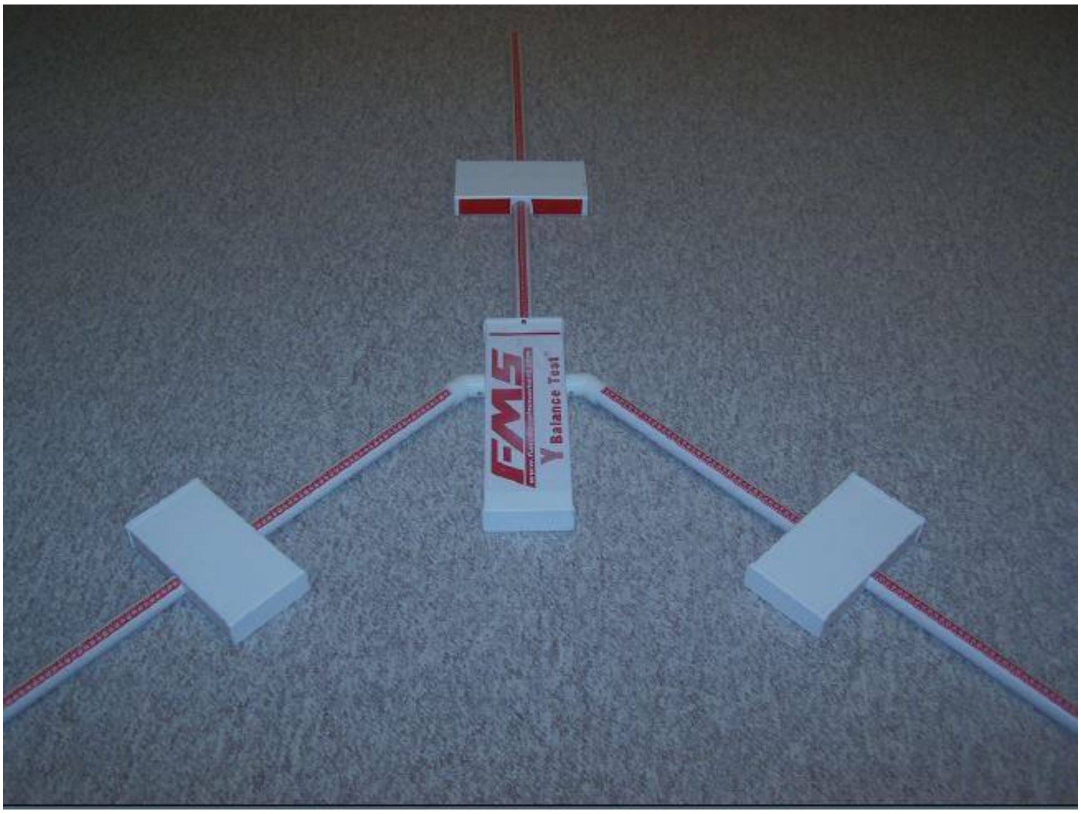

Figure 2-1. **Y-balance Test Kit ™**

Taken from Plisky et al., 2009 (144)

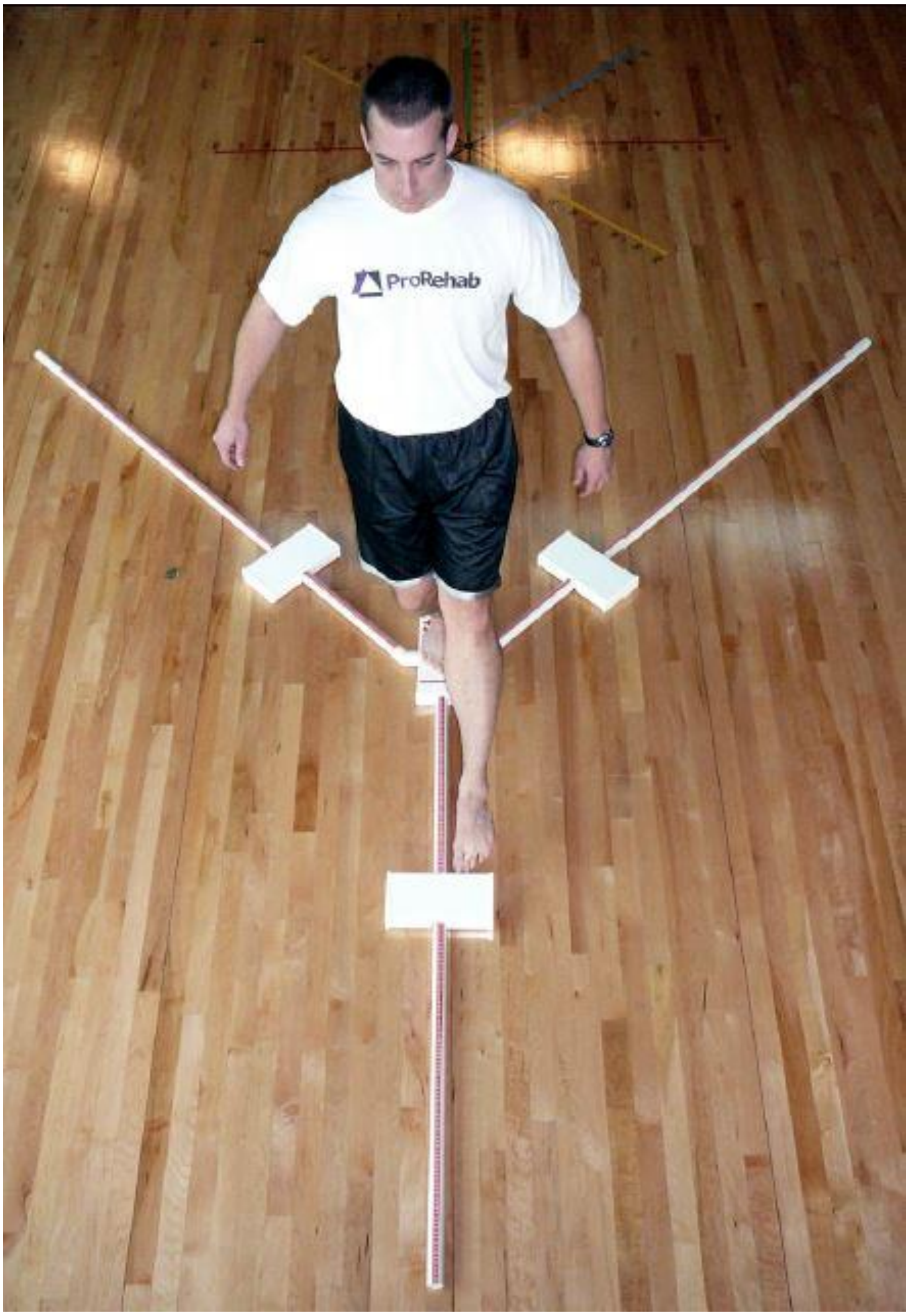

Figure 2-2. Anterior reach direction of Y-Balance test

Taken from Plisky et al., 2009 (144)

Figure 2-3. Posteromedial reach direction of Y-balance test

Taken from Plisky et al., 2009 (144)

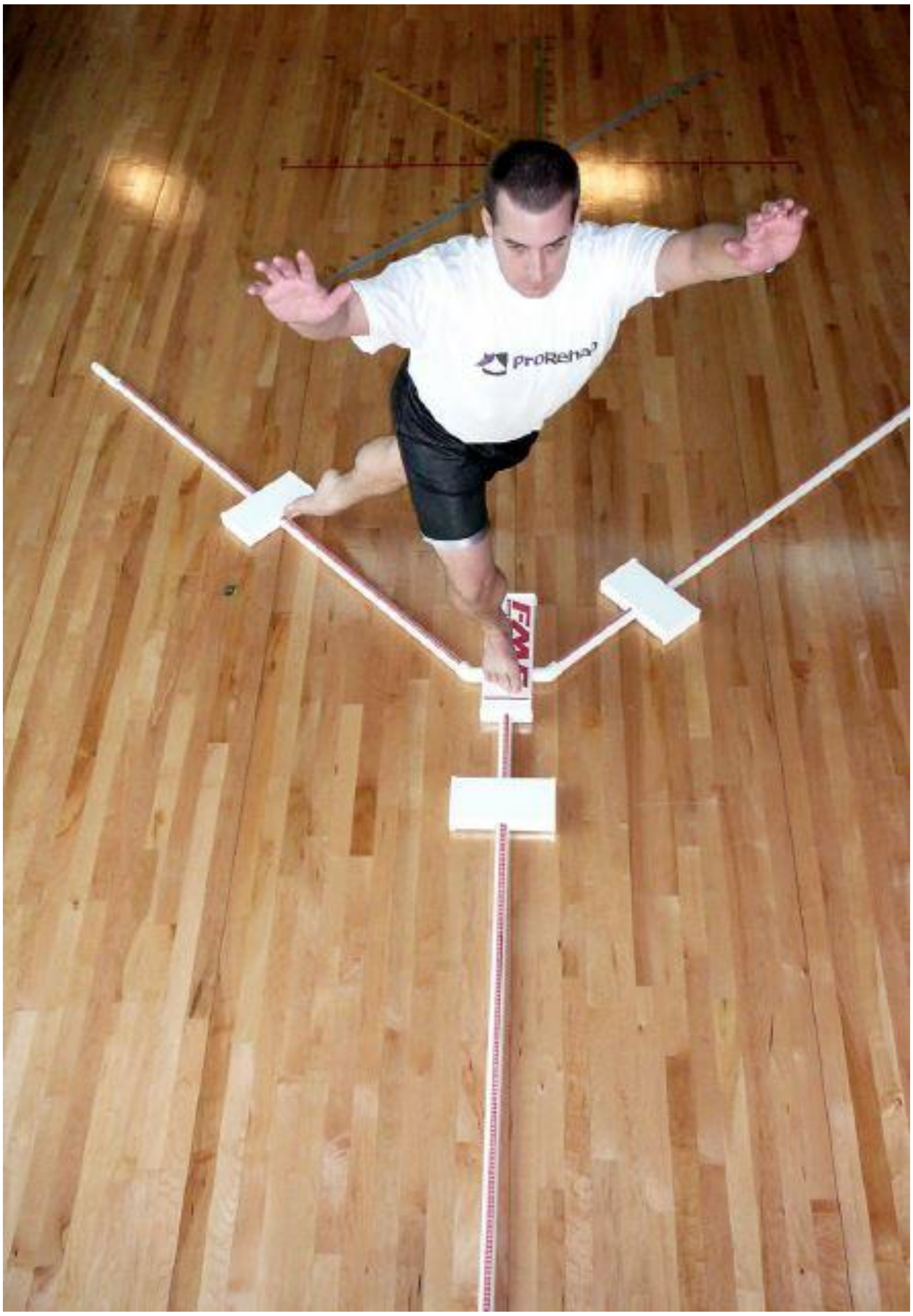

Figure 2-4. Posterolateral reach direction of Y-Balance test

Taken from Plisky et al., 2009 (144)

2.2.5. Reactive Strength

RS describes an individual's ability to complete a fast stretch-shortening cycle, explosively transitioning from an eccentric (braking) into a rapid concentric (propulsion) muscle contraction (146). The ability of an athlete to apply more force in a shorter amount of time is extremely beneficial in many sport and exercise settings (119). RS is commonly used to assess athletic ability, optimise training, reduce injury and monitor recovery (119). RS is commonly measured using two techniques within the literature to quantify an individual's plyometric stretch-shortening ability (147). The reactive strength index (RSI) is calculated from the height jumped (often derived from flight time) divided by the time spent on the ground developing the forces for the jump (ground contact time) (148). The reactive strength ratio (RSR) is calculated by diving the flight time of the jump by the ground contact time (148, 149). Due to this DJs have been commonly used in research to assess RS. In recent years research has begun to include the assessment of RS following exercise which results in muscle damage (15, 27).

RS was assessed using DJs from a 29cm box on to a force platform (Kistler 9281CA, Kistler Instruments Ltd.; Akon, United Kingdom); jump ground reaction forces were recorded at 1000Hz (Bioware, v3.21, Kistler Instruments Ltd.; Akon, United Kingdom). Participants were provided instruction and demonstration of the correct DJ technique. The technique was performed as suggested to ensure a "drop jump" is completed as opposed to a "depth jump" (117). The technical DJ model employed contained five distinct phases 1) step-off, 2) descent, 3) contact, 4) Take-off & 5) landing (117). Corrective cues were provided to participants to reduce the presence of common errors observed during the DJs (Figure 2-5) (117). Participants completed a minimum of 10 DJs during a familiarisation visit to ensure they were able to jump with appropriate technique; further jumps were completed if required to ensure correct and consistent technique. Each subsequent laboratory visit three warm-up DJs were performed prior to the main test and the investigator ensured DJ technique remained correct. Participants then completed three maximal DJs with hands on hips, separated by a 60s rest period. Any DJs with incorrect technique were discarded and repeated until three valid trials had been obtained. Take-off and landing were identified as the points where vertical ground reaction force descended or ascended past 20N (150). RSR was calculated by dividing flight time by ground contact time; flight time was calculated as the time between take-off and landing (148, 149). The maximum RSR value from the three jumps was taken and used in analysis (15, 27).

Phase	Key Points	Common Errors	Corrective Cues
Step-off 	1. The athlete should stand upright on a box with the hands placed on the hips. 2. The movement should be initiated by stepping out from the box with a single leg rather than jumping with both.	Stepping down from or jumping off the box.	*"step onto an invisible box"* *"step out"*
Descent 	1. As the athlete descends toward the floor, they should prepare for ground contact. 2. Limbs and trunk should be stiffened with the ankle in a neutral position to promote ankle stiffness. 3. A small amount of flexion in the knee and hip should be present.	Excessive forward trunk lean/ looking at the floor. Lack of stiffness in preparation for ground contact.	*"Look at a fixed point in front of you"* *"Be ready to push the floor away immediately"*
Contact Phase 	1. On ground contact, the feet should be shoulder width apart and the heels of the feet should remain off the floor. 2. The center of mass is likely to fall a small distance during ground contact due to a small amount of hip, knee and ankle flexion and should occur quickly before the movement is rapidly reversed.	Soft landing with excessive knee and hip flexion and very long ground contact times. Poor utilisation of elastic energy and SSC due to lack of preparatory stiffening for impact. Heels collapsing onto floor. Very stiff landing with little hip or knee flexion. Knee valgus	*"Bounce like a ball"* *"Imagine you are on a trampoline or pogo stick"* *"Try to be quiet on the floor"* *"Don't squash the grape under your heel"* *"Bounce like a spring"* *"Stretch an imaginary band that is around your knees"*
Take-off 	1. At the point of take-off, the toes should be the final part of the foot to leave the floor. 2. The hip, knee and ankle should all be fully extended as the result of an explosive triple extension in a vertical direction.	Lack of triple extension. Lack of synchronisation of triple extension	*"Look over the fence"* *"Imagine you are being stretched"* *"Be like a string being pulled tight"*
Second Landing 	1. Initial contact is made by the forefoot, followed shortly by the heel, meaning weight distribution will move to the rear foot as more of the landing force is absorbed. 2. The athlete should land softly assuming a half-squat position with knees aligned over the toes and feet shoulder distance apart.	Heavy landing with poor force absorption. Poor weight distribution through foot, staying predominantly through the forefoot. There is large horizontal displacement between the first and second landing.	*"don't make a sound"* *"sit onto the chair behind you"* *"land behind this line"*

Figure 2-5. Technical model for the drop jumps with common errors and example corrective cues.

Taken from Pedley et al., 2017(117)

2.2.6. Readiness to Exercise

Limited research (discussed in section 1.5.6) has investigated how psychological recovery may be affected following muscle damaging exercise (63, 71, 78). This research has only employed basic measures by which individuals report their recovery. In elite sport, self-report measures are often favoured over physiological and performance outcomes, as they provide cost effective and practical assessments to administer (122). Self-report measures monitor the response to training by examining mood states, perceived internal load and recovery-stress states. The POMS and RESTQ-sport present the most commonly used valid and reliable assessments within the literature, used for monitoring athletes (123). However, though used extensively, neither the POMS or RESTQ-sport address the current “right now” recovery-stress state of an individual in a multi-dimensional manner(122). The Acute Recovery and Stress Scale (ARSS) and Short Recovery and Stress Scale (SRSS) were developed to address this issue (151, 152). The ARSS and SRSS assess emotional, physiological and mental aspects of recovery and stress. Research employing these assessments may provide more insight into self-reported recovery following muscle damaging exercise.

The SRSS is a valid and reliable instrument, which has been shown to have good construct validity with other commonly used established instruments (152-154). The SRSS was initially created in German but has recently been validated for use with native English-speaking populations (122, 155). The short (8-item) nature of the SRSS is ideal when looking to assess individuals on a frequent basis (i.e., daily) (155). The SRSS (Appendix G) was used to assess the current recovery-stress state of participants and individuals were requested to complete the questionnaire as they felt "right now".

2.2.7. Rating of Perceived Exertion

RPE is a method for describing the physiological intensity and individual perceives themselves to be working at. The RPE scale is the most widely used assessment of perceived exertion within research (156). The scale is comprised of a fifteen-point vertical scale, ranging from "6 – no exertion" to "20 – maximal exertion". The RPE scale has validity with physiological measures (heart rate, blood lactate concentration, % $\dot{V}O_2max$, $\dot{V}O_2$, respiration rate) (157). The RPE scale has been shown to correlate with heart rate (HR) and blood lactate concentration, independent of sex, age, physical activity status and exercise modality (158, 159). Participants were familiarised with the RPE scale and how to rate their exertion prior to commencing exercise.

2.2.8. Heart Rate

HR is used extensively as a simple measure to monitor intensity during exercise. HR (Polar RCX5, Polar Electro Oy; Kempele, Finland) was recorded at 5-s intervals for the duration of exercise.

2.2.9. $\dot{V}O_2$peak

A percentage of $\dot{V}O_2$max or $\dot{V}O_2$peak achieved during an incremental exercise test (IXT) has frequently been used to determine the relative intensity at which individuals should complete subsequent downhill running (160-162). When completing a single exercise test the highest recorded oxygen uptake value represents a peak response, providing an estimate of $\dot{V}O_2$peak (163). $\dot{V}O_2$peak (ml.kg.min^{-1}) was determined from breath-by-breath online gas analysis (Oxycon Pro, Jaeger; Hoechberg, Germany) during an IXT. The online gas analyser was calibrated before each procedure using a certified gas analyser. The IXT was performed on a motorised treadmill (Saturn, HP Cosmos; Nussdorf, Germany) using 1-min stages, with 1 km.h^{-1} increments, starting from 8 km.h^{-1}, until participants achieved volitionary exhaustion (164). Participants were requested to report well rested, nourished and hydrated and wearing appropriate comfortable footwear and clothing. Participants were requested to avoid eating 2 h before the IXT and to abstain from caffeine, alcohol and strenuous exercise 24 h before the testing. The temperature of the laboratory was controlled at 20-22° C. Strong verbal encouragement was consistently provided for all participants, to assist in maximum effort being given. $\dot{V}O_2$peak was calculated from the mean maximal oxygen consumption over a 30-s period (165).

2.3 Statistical Analysis

A priori power analyses (G∗POWER 3.1 Software, Düsseldorf, Germany) were conducted to determine significant power at an α-level of 0.05. Means, standard deviations and effect sizes were used to determine appropriate sample sizes for individual experimental chapters; these are discussed individually in more detail within the relevant section.

IBM SPSS v25.0 (IBM Corp., USA) was used for all the presented statistical analysis with the exception of repeated measures correlations (RMCORR). One-way repeated measures Analysis of Variance (ANOVA) were used to determine the effect of time. Two-way mixed ANOVA were used to determine any effect of time, condition and time x condition interaction. Normality probability plots from residuals were inspected and confirmed that samples were normally distributed. The sphericity of data was assessed using Mauchly's test of sphericity; if violated, a corrected test was reported (Greenhouse-Geisser). Standardised residuals were calculated and assessed to identify potential outliers (> 3 SD). If values were identified as > 3 SD, the analysis was conducted with the outliers removed, to determine if this had a meaningful influence on the results; no outlier data points were omitted from any of the final analysis presented in this thesis. Post-hoc analysis for time was conducted using pairwise comparisons with a Bonferroni correction factor. Analysis of Covariance (ANCOVA) were used in place of ANOVA when there was a need to account for differences between conditions in pre-exercise scores. Paired samples t-tests were used to compare between measures pre-exercise and immediately post exercise; where t-tests were used the heterogeneity of the data was assessed using Levene's test for equality of variances.

RMCORRs were used to investigate repeated associations between outcomes over time (166, 167). RMCORR is a statistical technique for determining the common within-individual association for paired measures which are assessed on two or more occasions (167). Unlike standard correlation techniques, RMCORR handles repeated measures without violating independence assumptions or requiring the aggregation of data. RMCORR statistics were conducted using RStudio v1.2.5 (Rstudio, Inc., Boston, USA) using the rmcorr package (v.0.30) (167).

An α-level of 0.05 was used to signify statistical significance across all experimental chapters. In addition to *p* values, effect sizes and confidence interval statistics were used to identify the magnitude of effects. Additional statistical analysis specific to an individual experimental chapter is provided in more detail within the relevant section.

2.3.1. Imputation of Missing Data

Missing data points were imputed using 'Expectation Maximisation Imputation' following a missing value procedure to assess whether data was missing at random or not. Expectation maximisation is an iterative method to compute maximum likelihood estimates from incomplete data series (168). Little's MCAR test was initially conducted to assess whether data was missing at random or whether there were patterns to the missing data. The null hypothesis for Little's MCAR test is that data are missing completely at random. If Little's MCAR test is non-significant, estimation maximisation imputation can be run to complete the incomplete data series (169).

3. The Effect of Downhill Running Conditions on Muscle Damage in Recreationally Active Adults

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A version of this section has been published as a research article. The reference for this is:

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3.1 Introduction

As discussed, (section 1.1) eccentric (lengthening) muscle actions have been shown to produce more muscle damage than concentric or isometric actions (3). Previous research (section 1.4) has used activities such as isolated eccentric contractions of localised muscle groups (elbow flexors / knee extensors) or exercises comprising of large amounts of eccentric muscle activity (e.g., eccentric squats), to investigate recovery from exercise-induced muscle damage (2, 4). These activities are known to cause muscle damage, however, they are not representative of exercise regularly conducted in day-to-day life. DR provides a functional activity, containing exaggerated eccentric muscle activity, which is more indicative of movements in real-world sport and exercise. DR requires the muscle to work over a greater length and involves more angle changes than level running (162, 170). This leads to increased mechanical stress as brake force is generated during the eccentric actions and results in extensive muscle damage occurring (114). Therefore, investigating recovery from muscle damage caused by DR appears a more ecologically valid method to provide useful information which can be applied to exercise activities of daily living.

There is no consensus about which DR protocol is most effective in causing muscle damage. DR has been conducted at varying gradients (-4 to -16%) (26, 171), over continuous (20-45 min) (26, 111, 161, 172, 173) or repeated (5-8 min) (94, 171, 174-178) durations and at varying intensities: velocity at $\dot{V}O_2max$ / peak (50-80%) (160-162), HR max (80%) (175), predefined speed or a maximum tolerable velocity (111). DR has been conducted using participants of varying fitness levels, ranging from healthy inactive / untrained individuals (26, 111), to highly active well-trained endurance athletes (173, 179). Therefore, it is unclear what severity, intensity and duration of DR is most appropriate to produce muscle damage. Understanding what DR conditions may be most effective at producing muscle damage in recreationally active adults, will allow for comparison of recovery with exercise resembling activities of daily living.

As discussed (section1.1), the direct assessment of muscle damage is highly invasive (i.e., muscle biopsies) or requires the use of expensive equipment (MRI) which may not always be available. Indirect markers are commonly used to quantify the magnitude and time course of muscle damage (3, 4). The loss of force-generating capacity is one of the most valid and reliable indirect indicators of exercise-induced muscle damage (4, 13). Concentric and eccentric exercise protocols both result in an immediate reduction in force-generating capacity. Following concentric activity, force generation returns to pre-exercise within a few hours, however, after eccentric activities this recovery is prolonged, indicating the presence of muscle damage (4). DR has been shown to reduce muscle force-generating capacity of between 10-30%, before returning towards pre-exercise within 4-7 days (4, 94, 111, 161, 170, 175, 180, 181). Muscle soreness provides another commonly used indirect indicator of muscle damage and has been shown to increase significantly following DR, peaking 24-48 h post exercise, before returning to pre-exercise within 5 days (94, 111, 161, 162, 174-176, 179-183).

3.1.1. Aims & Research Questions

The purpose of this research is to determine the most appropriate DR conditions to induce muscle damage in recreationally active adults. The aim is to investigate how the duration and gradient of DR affect the magnitude of muscle damage response, assessed using indirect markers. The investigation will have the following research questions:

1) Does the duration and gradient of DR affect the muscle damage response?

3.2 Materials and Methods

3.2.1. Participants

Participants were 12 healthy, recreationally active male adult volunteers, exercising two-five times per week (Table 3-1). Participants had not taken part in lower limb exercise activities which would be expected to confer protection against downhill running in the last 6-months. Participants were screened for contraindicators to exercise using the Physical Activity Readiness Questionnaire (Par-Q) (Appendix H). As described previously (section 2.1), ethical approval to perform the research was granted by the University of Essex ethics committee and written informed consent was provided by all participants, prior to commencing experimental work.

Table 3-1. Participant demographics by downhill running condition.

Condition	Age (years)	Stature (m)	Mass (kg)	BMI ($kg \cdot m^2$)	VO2peak ($ml \cdot kg^{-1} \cdot min^{-1}$)
DR10	24.5 ± 7.4	1.76 ± 0.10	73.6 ± 4.2	23.8 ± 2.7	55.6 ± 7.5
DR12	24.8 ± 7.3	1.74 ± 0.07	70.7 ± 9.2	23.1 ± 1.7	51.4 ± 6.8
DR15	24.1 ± 6.4	1.77 ± 0.07	72.7 ± 5.8	23.3 ± 1.8	54.2 ± 6.1

Note: DR10 = 45 min running downhill at 10% gradient (n=4), DR12 = 45 min running downhill at 12% gradient (n=4), DR15 = 30 min running downhill at 15% gradient (n=4); ANOVA run to confirm no difference ($p > 0.05$) between condition for all outcomes

3.2.2. Procedures

During visit 1 (Figure 3-1) participants completed an incremental exercise test (IXT) to exhaustion (detailed in 2.2.9), followed by a protocol to familiarise them with all outcome measures. One-week later participants completed pre-exercise measurements for isometric force and muscle soreness (Visit 2) and were then randomly allocated to one of three DR conditions. Immediately following the DR (post) a measurement of isometric force was obtained. Participants attended the lab 24 h (Visit 3) and 48 h (Visit 4) post DR to assess isometric force and muscle soreness status. The laboratory was kept at a consistent temperature (20 °C) and participants attended at the same time of day (± 1 h) across all visits, to minimise the influence of circadian rhythm on performance (184, 185). Participants were requested to refrain from completing structured exercise activities while participating in the research.

Participants completed one of three DR conditions on the motorised treadmill (Saturn, HP Cosmos; Nussdorf, Germany). The intensity of the downhill run was at 70% of the velocity at which $\dot{V}O2peak$ was achieved during the IXT. The three DR conditions were 30 min at -15% gradient (DR15), 45 min at -12% (DR12) and 45 min at -10% (DR10); chosen based on commonly used intensities, gradients and durations of DR conditions within the literature and following preliminary pilot investigations (94, 111, 114, 160, 162, 172, 173, 177, 178, 180, 181, 183, 186). Mean HR was calculated from 5-s interval recordings throughout each downhill run.

3.2.3. Measures

i. Force Loss

Force loss was assessed as previously described in section 2.2.1 using maximal isometric contractions.

ii. Muscle Soreness

Muscle soreness was assessed as previously described (section 2.2.2) using a visual analogue scale. Muscle soreness ratings were assessed by participants rating the pain or discomfort they perceived when completing the MVIC.

iii. Heart Rate

Heart rate was assessed for the duration of the IXT and DR as previously described in section 2.2.8.

3.2.4. Statistical Analysis

An a priori power analysis was conducted as previously described (section 0) to determine significant power using published DR force loss data, revealing a total required sample size of 12 participants (94, 111, 180, 181). Mean ± standard deviation (SD), absolute and change from pre-exercise values were calculated and presented in tables (Microsoft Excel, Microsoft Office 365 Pro Plus). Statistical analysis was conducted using ANOVA and ANCOVA as previously described in section 0. One-way ANOVA were used to check there were no differences between condition in demographic variables. Two-way mixed method ANOVA were used to investigate any main effect of time, condition or time x condition interaction, for force loss and muscle soreness. Post-hoc analysis for time was completed using pairwise comparisons with a Bonferroni correction factor. One-way ANCOVA were conducted to determine differences between condition while controlling for pre-exercise. Estimated marginal means (EMM) were presented to illustrate change in force loss and muscle soreness after controlling for pre-exercise. Effect sizes from ANOVA and ANCOVA were reported as partial Eta squared (ηp^2).

Figure 3-1. Schematic of experimental design to compare downhill running conditions

3.3 Results

3.3.1. Force Loss

All DR conditions resulted in a reduction in force immediately post-exercise compared to pre-exercise ($F = 22.66$, $p = 0.001$, $\eta p^2 = 0.72$; Table 3-2); there was no difference between conditions ($F = 0.22$, $p = 0.807$, $\eta p^2 = 0.05$) or interaction of time x condition ($F = 0.11$, $p = 0.895$, $\eta p^2 = 0.02$). There was a main effect of time for isometric force ($F = 7.20$, $p = 0.005$, $\eta p^2 = 0.45$), with reduced force at 24 h ($p = 0.014$) compared to pre-exercise but no difference between pre-exercise and 48 h ($p = 1.000$). There was no effect of condition ($F = 0.20$, $p = 0.819$, $\eta p^2 = 0.04$) or interaction of time x condition ($F = 0.27$, $p = 0.894$, $\eta p^2 = 0.06$) for isometric force. When controlling for pre-exercise (Figure 3-2) there was no difference in isometric force between conditions at 24 h ($F = 0.06$, $p = 0.942$, $\eta p^2 = 0.02$) or 48 h ($F = 0.64$, $p = 0.554$, $\eta p^2 = 0.14$).

3.3.2. Muscle Soreness

There was a main effect of time for muscle soreness ($F = 8.52$, $p = 0.002$, $\eta p^2 = 0.49$), with increased soreness at 24 h ($p = 0.038$) compared to pre-exercise but no difference between pre-exercise and 48 h ($p = 0.499$; Table 3-2). There was no main effect of condition ($F = 1.89$, $p = 0.206$, $\eta p^2 = 0.29$) or interaction of time x condition ($F = 1.61$, $p = 0.216$, $\eta p^2 = 0.26$) for muscle soreness. When controlling for pre-exercise (Figure 3-2) there was no difference in muscle soreness between conditions at 24 h ($F = 0.64$, $p = 0.554$, $\eta p^2 = 0.14$) or 48 h ($F = 0.91$, $p = 0.441$, $\eta p^2 = 0.19$).

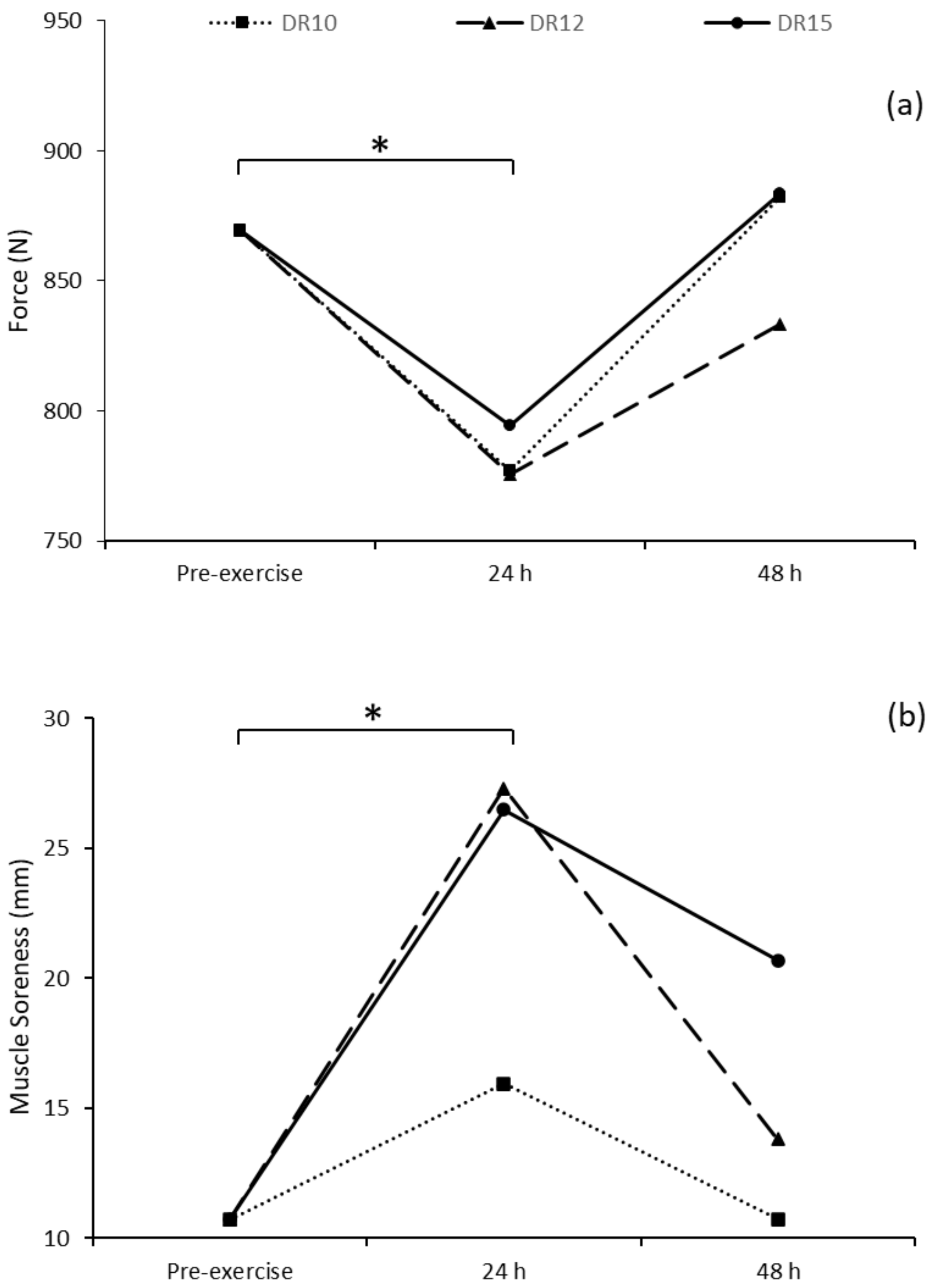
3.3.3. Heart Rate

There was no main effect for condition on HR ($F = 0.20$, $p = 0.821$, $\eta p^2 = 0.03$). Mean HR was 145 ± 15 $b \cdot min^{-1}$, 144 ± 14 $b.min^{-1}$ and 140 ± 1 $b.min^{-1}$ in DR15, DR12 and DR10 conditions, respectively.

Table 3-2. Isometric knee extensor force and muscle soreness pre-exercise and change from pre-exercise (Δ) values (mean ± SD) following three downhill running conditions.

	Condition	Pre-exercise	Post	Δ Post	24 h	Δ 24 h	48 h	Δ 48 h
Isometric Force (N)	**DR10**	939 ± 365	727 ± 307	-212 ± 170	843 ± 385	-92 ± 49	951 ± 326	12 ± 69
	DR12	832 ± 270	657 ± 185	-175 ± 114	740 ± 253	-92 ± 27	796 ± 329	-36 ± 79
	DR15	838 ± 195	616 ± 112	-222 ± 155	764 ± 158	-74 ± 128	852 ± 202	14 ± 52
Muscle Soreness (mm)	**DR10**	3.3 ± 3.2	-	-	6 ± 7	3 ± 5	3 ± 4	-1 ± 3
	DR12	18.4 ± 19.1	-	-	37 ± 25	19 ± 8	22 ± 22	4 ± 6
	DR15	10.7 ± 13.2	-	-	26 ± 23	16 ± 22	19 ± 18	16 ± 10

Note: DR10 = 45 min running downhill at 10% gradient (n=4), DR12 = 45 min running downhill at 12% gradient (n=4), DR15 = 30 min running downhill at 15% gradient (n=4)



* significant main effect of time (p<0.05); Error bars omitted from figure to aid clarity of interpretation; DR10 = 45 min running downhill at 10% gradient (n=4), DR12 = 45 min running downhill at 12% gradient (n=4), DR15 = 30 min running downhill at 15% gradient (n=4)

Figure 3-2. Isometric knee extensor force (a) and muscle soreness (b) following the three downhill running (DR) conditions when controlling for pre-exercise (EMM).

3.4 Discussion

The aim of this research was to investigate how the conditions (gradient and duration) of DR affect the magnitude of muscle damage caused in recreationally active adults. Immediately post exercise all three DR conditions resulted in a significant reduction (20-25%) in force-generating capacity. The force reduction was similar between conditions, indicating all three caused a similar level of muscle fatigue. One day later a significant reduction in force remained (8-10%) and this was similar across all conditions. The force loss still evident at 24 h indicates that all conditions were effective at causing muscle damage. The reductions observed in force loss immediately post exercise and at 24 h are in line with those previously reported following DR (4, 94, 111, 161, 170, 175, 180, 181). At 48 h force generation was no longer impaired, indicating muscle damage had recovered across all conditions.

A significant increase (12%) was observed in muscle soreness 24 h post exercise. At 48 h the increase was no longer present, suggesting muscle soreness had recovered. The observed increase at 24 h followed by decrease at 48 h in muscle soreness, is similar to those previously reported following DR (94, 111, 161, 162, 170, 175, 176, 179-183). There was no significant difference between conditions at any time, suggesting all conditions resulted in similar muscle soreness.

Taken together, the observed force loss and muscle soreness indicate that all three DR conditions were effective at causing significant muscle damage 24 h post exercise, before recovery was observed at 48 h. Interestingly it would appear that increased duration and gradient do not increase the extent of muscle damage, as may have been intuitively expected. However, the 30-min condition is able to produce the same muscle damage in less time, therefore reducing the time commitment for both investigator and participant. Additionally, there was no difference in average HR across the conditions, suggesting running downhill at the steeper gradient did not involve additional cardiovascular strain. Therefore, it is likely the shorter condition would be more amenable to participants, especially if working with those not accustomed to running for prolonged periods.

Laboratories provide a controlled environment where recovery from exercise can be monitored. However, the protocols used do not necessarily replicate activities as they are undertaken in the "real world". As discussed previously (section1.4), research has begun to move away from laboratory-based muscle damage protocols and investigate recovery from sport activities (15, 16, 27, 28, 101-103). It is important to first establish laboratory-based protocols which can be compared with "real world" activities to better understand the differences / similarities in recovery. Appropriate protocols (such as DR) are required, which are comparable in duration and intensity to common activities. Current Government guidelines recommend activities be conducted in 30-min bouts (187). Therefore, the 30-min DR condition presented here is ideal for comparisons with common 30-min exercise activities. This approach will ensure scientific rigour is maintained when carrying out muscle damage research in more ecologically valid environments.

3.4.1. Conclusions

In summary, all three DR conditions were effective in causing a similar magnitude of muscle damage when completed by recreationally active adults. Interestingly, the 30-min condition completed at a steeper gradient (15%), produced the same muscle damage response in less time, without requiring individuals to work at a greater intensity. Therefore, researchers looking to induce muscle damage using DR should employ the 30-min protocol. This will offer time-saving benefits and may be superior for individuals not accustomed to prolonged periods of running.

4. Functional and Psychological Recovery Following Conventional Laboratory-Based Muscle Damaging Exercise

4.1 Introduction

As discussed (section 1.1), it is well established that performing unaccustomed strenuous exercise is associated with causing muscle damage (2). Eccentric (lengthening) muscle actions are associated with causing a greater magnitude of muscle damage compared with concentric or isometric contractions (3). Research investigating muscle damage, uses exercise which involves isolated eccentric contractions (e.g., elbow flexors) or exercises comprising of exaggerated eccentric actions, such as DR, to cause muscle damage (4). DR offers more functional activity than isolated eccentric contraction exercises. During DR eccentric muscle actions are accentuated as the muscle works at a greater length, increasing mechanical stress and resulting in muscle damage (162, 170).

Direct quantitative assessment of muscle damage is challenging as it requires analysis of invasive and painful muscle biopsies or the use of expensive magnetic resonance imaging (MRI). Indirect markers are used extensively to quantify muscle damage following exercise. As discussed (section 1.5.1), one of the most valid and reliable indirect measures of muscle damage is the loss of muscle strength (4, 13). DR protocols have been shown to produce a reduction in muscle force of between 10-30% immediately post exercise, which returns to pre-exercise levels within 4-7 days (4, 94, 111, 161, 170, 175, 180, 181). Muscle soreness and myofibrillar proteins present in the blood (discussed previously in section 1.5.2 & 1.5.3), provide two additional commonly used indirect indicators of muscle damage (2-4). Following DR, muscle soreness and CK have been shown to increase significantly, peaking 24-48 h post exercise, returning towards pre-exercise around 5-7 days post exercise (111, 175, 176, 180, 181, 183). The accurate assessment of force loss requires laboratory equipment and the measurement of CK is invasive, making the assessment of muscle damage in day-to-day sport and exercise settings challenging.

Surprisingly (discussed in section 0), there has been limited research assessing functional outcome measures following conventional muscle damaging modes of exercise (e.g., DR) which have been used extensively within the literature. Functional assessments may provide proxy indicators for muscle damage which can be practically implemented and monitored in real world sport & exercise settings. In athletes, having balance ability has been associated with performance and risk for injury (120, 121, 188). Dynamic balance has been shown to be impaired following repeated sprints which caused muscle damage (16). As discussed (section 2.2.5), the ability to apply more force in a shorter amount of time, is extremely beneficial in many sport and exercise settings and is commonly used to assess athletic ability in sport. RS has been shown to be impaired following repeated sprint and dance exercise which caused muscle damage (15). ROM (discussed in section 1.5.4) has been assessed extensively and shown to be impaired following isolated eccentric muscle damaging exercise protocols (4, 13). Following repeated sprints ROM was shown to be significantly impaired between 24-72 h post exercise (16, 115). Therefore, it appears when exercise is completed which results in muscle damage, all functional outcomes may be impaired over a similar time-course. Currently no research has investigated how functional outcomes respond following conventional laboratory-based muscle damaging exercise (e.g., DR). This research would provide further insight into how functional outcomes are affected following a mode of muscle damaging exercise which is well documented.

As discussed previously (section1.5.6), there is very limited research which has considered how muscle damaging exercise may affect how ready an individual feels to take part in further exercise. Individuals reported feeling significantly less ready to conduct an incremental exercise test 48 h after completing muscle damaging exercise of the knee extensors and flexors (189). Additionally, individuals reported feeling less recovered up to 72 h post completing muscle damaging exercise involving the knee flexors and shoulders (71, 78). These initial investigations suggest that EIMD causes individuals to feel less recovered and / or ready to complete further exercise. Research exploring self-reported recovery / readiness to exercise following EIMD has involved individuals rating how they feel on simple single scale assessments. Research employing a more in-depth assessment would provide further insight into the relationship between psychological and physiological recovery following muscle damaging activity and how this influences an individual's ability to complete further exercise.

The SRSS, is a recently validated psychological instrument which assesses recovery and stress states (152). The SRSS was shown to be a subjective measure which reflected fatigue and recovery over a 6-day period, following strength and high intensity interval training (153). The SRSS therefore provides an instrument which can quantify psychological recovery and be used to determine how muscle damaging exercise affects readiness to exercise. Investigating readiness to exercise following common muscle damaging activity (DR) may provide insight which can inform monitoring tools used in sport and exercise settings.

4.1.1. Aims & Research Questions

The purpose of this investigation is to determine if functional and psychological outcomes are impaired following a conventional laboratory-based mode of muscle damaging exercise (DR). Associations will be investigated between indirect markers of muscle damage and functional and psychological outcomes to establish their utility as accessible proxy indicators for muscle damage. The investigation will have the following research questions:

1) Does completing DR result in muscle damage?

2) Are functional outcomes affected by completing DR?

3) Are self-reported psychological outcomes affected by completing DR?

4) Are the responses of functional and psychological outcomes associated with the response of common indirect markers or muscle damage?

4.2 Methods

4.2.1. Participants

Participants (Table 4-1) were 16 (12 Experimental) healthy male adult volunteers, who were recreationally active taking part in structured exercise two-five times per week. Participants had not taken part in lower limb exercise activities which would be expected to confer protection against downhill running in the last 6-months. Participants for the control condition were recruited following the completion of the experimental conditions. Participants were screened for contraindicators to exercise using the PAR-Q (Appendix H). As described (section 2.1), ethical approval to perform the research was granted by the University of Essex ethics committee and written informed consent was provided by all participants, prior to commencing experimental work

Table 4-1. Participant characteristics by condition.

Condition	Age (years)	Stature (m)	Mass (kg)	BMI ($kg \cdot m^2$)	VO2peak ($ml \cdot kg^{-1} \cdot min^{-1}$)
Experimental	27.6 ± 6.9	1.80 ± 0.10	84.4 ±11.0	26.6 ± 4.1	48.8 ± 9.2
Control	30.5 ± 4.8	1.77 ± 0.10	80.6 ± 11.8	25.8 ± 3.9	-

Note: Experimental (n = 12); Control (n = 4)

4.2.2. Procedures

At the initial laboratory visit (Visit 1), the experimental condition completed an IXT to exhaustion (described in section $\dot{V}$O2peak), followed by familiarisation with all outcome measures (Figure 4-1). One-week post the IXT participants attended the lab (Visit 2) to complete pre-exercise measurements. Outcome measures were tested in the following order: 1) SRSS 2) CK 3) ROM 4) MVIC & Muscle Soreness 4) RS 5) Balance. Following pre-exercise assessments, the DR was conducted by the experimental condition; the control condition completed no DR and were only assessed for outcome measures at all time points; ROM and CK were not assessed for the control condition. Immediately post DR the experimental condition completed another MVIC. Participants attended the lab again at 24 h (Visit 3), 48 h (Visit 4), 72 h (Visit 5) and 96 h (Visit 6) post the DR. The laboratory was kept at a consistent temperature (20 °C) and participants attended at the same time of day (± 1 h) across all visits, to minimise the influence of circadian rhythm on performance (184, 185). Participants were requested to refrain from completing structured exercise activities while participating in the research.

i. Downhill Running

Participants completed the DR protocol on a motorised treadmill (Saturn, HP Cosmos; Nussdorf, Germany). The downhill run was completed at a gradient of -15% for 30 min at 70% of the velocity achieved at $\dot{V}O_2$peak. This protocol was selected following the investigations discussed in the previous section (3).

4.2.3. Measures

i. Isometric Force

Isometric knee extensor force was assessed using maximal isometric contractions as described previously in section 2.2.1.

i. Muscle Soreness

Muscle soreness was assessed using a VAS as previously described in section 2.2.2. Muscle soreness ratings were assessed by participants rating the pain or discomfort they perceived when completing the MVIC.

ii. Creatine Kinase

CK was assessed from venous blood samples as previously described in section 2.2.3. CK was not assessed for two participants, as they did not wish to have venous blood samples taken.

iii. Dynamic Balance

Balance was assessed using the Y-Balance test as previously described in section 2.2.4.

iv. Reactive Strength

RS was determined using the RSR from DJs as previously described in section 2.2.5.

v. Range of Movement

Range of movement was determined in the right ankle using the knee to wall test using a weight-bearing lunge (190). The angle was then measured using a bubble inclinometer. The top of inclinometer was aligned vertically with the tibial tuberosity and the site of placement marked for subsequent visits.

vi. Readiness to Exercise

Self-reported readiness to exercise was measured using the SRSS as previously described in section 2.2.6.

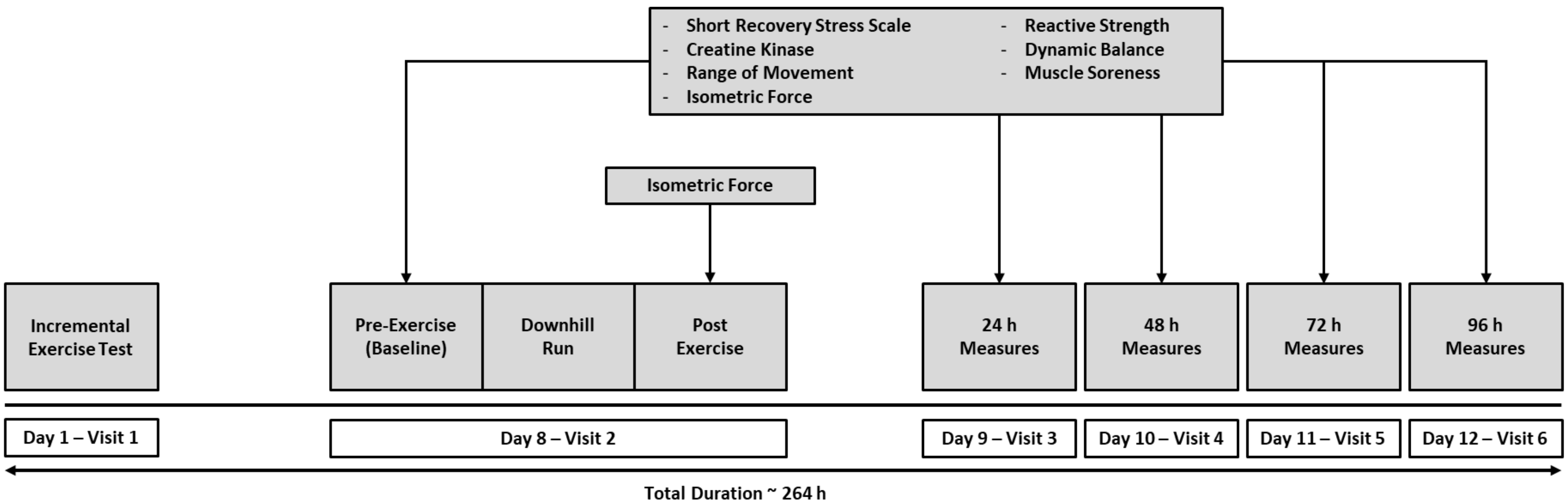


Figure 4-1. Schematic representation of the experimental protocol used to monitor recovery up to 96 h post downhill running.

4.2.4. Statistical Analysis

An a priori power analysis was conducted as described (section 0) to determine significant power using published force loss data from DR investigations, revealing a required sample size of 4 participants per condition (94, 111, 180, 181). Mean ± 95% confidence intervals were calculated and presented in tables and figures (Microsoft Excel, Microsoft Office 365 Pro Plus). Statistical analysis (SPSS v25.0) was conducted using an alpha level of 0.05. A paired samples t-test was used to determine differences between MVIC pre-exercise and immediately post exercise. One-way ANOVA (1 x 5) were used to determine the main effect of time on all outcome measures within each condition, as described in section 0. Effect sizes from ANOVA were reported as partial Eta squared (ηp^2) (191). Mean difference, 95% confidence intervals and effect sizes (Cohen's *d*) were calculated for change from pre-exercise at all time points (192, 193). RMCORR were used to evaluate associations over time between indirect markers of muscle damage and functional and readiness outcomes (described in section 0). Descriptive statistics for all measures across both conditions, at all-time points, are provided in Appendix I.

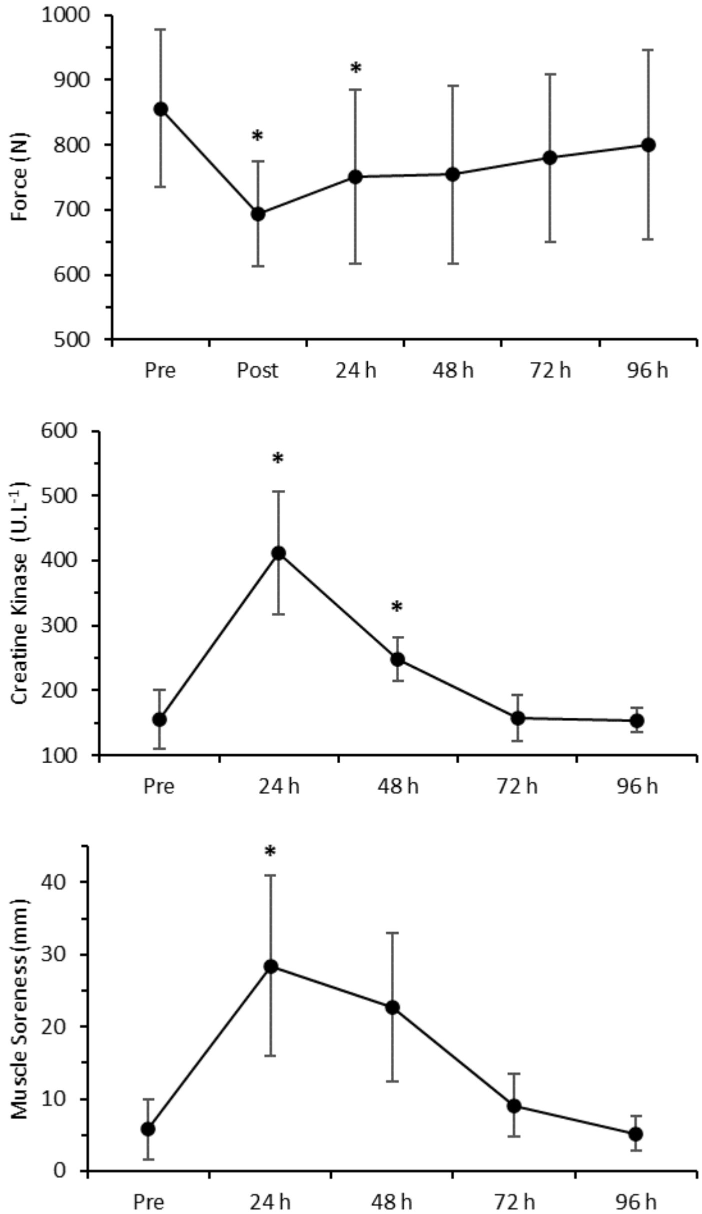
4.3 Results

4.3.1. Indirect Markers of Muscle Damage

Force was significantly reduced immediately post exercise compared to pre-exercise in the experimental condition ($t = 5.11$, $p = 0.001$, $d = 1.00$). There was a main effect for time on force loss ($F = 3.86$, $p = 0.009$, $\eta p^2 = 0.26$), CK ($F = 37.42$, $p = 0.001$, $\eta p^2 = 0.81$) and muscle soreness ($F = 13.24$, $p = 0.001$, $\eta p^2 = 0.55$) in the experimental condition (Figure 4-2). Post-hoc analysis (Table 4-2) revealed force ($p = 0.007$) was reduced and CK ($p = 0.001$) and muscle soreness ($p = 0.003$) increased 24 h post exercise compared to pre-exercise; CK remained elevated ($p = 0.001$) 48 h post exercise. There was no main effect for time on force loss ($F = 1.40$, $p = 0.293$, $\eta p^2 = 0.32$) or muscle soreness ($F = 1.43$, $p = 0.283$, $\eta p^2 = 0.32$) in the control condition.

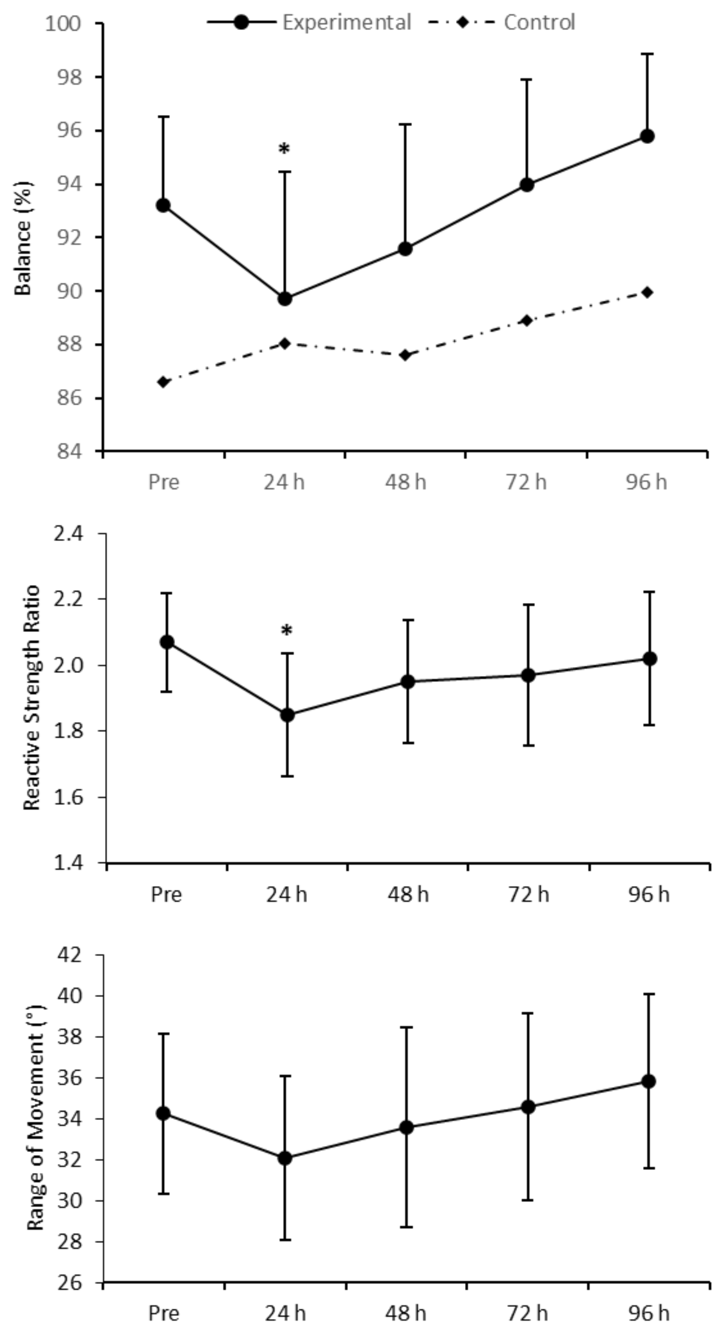
4.3.2. Functional Performance

There was a main effect for time on balance ($F = 14.69$, $p = 0.001$, $\eta p^2 = 0.57$), RS ($F = 4.73$, $p = 0.012$, $\eta p^2 = 0.30$) and ROM ($F = 5.14$, $p = 0.002$, $\eta p^2 = 0.32$) in the experimental condition (Figure 4-3). Post-hoc analysis (Table 4-2) revealed balance ($p = 0.003$) and RS ($p = 0.004$) were reduced from pre-exercise at 24 h post exercise. There was a main effect for time on balance in the control condition ($F = 4.83$, $p = 0.015$, $\eta p^2 = 0.62$). Post-hoc analysis () revealed balance was elevated from pre-exercise at 72 h ($p = 0.036$) and 96 h ($p = 0.056$). There was no main effect for time on RS ($F = 3.52$, $p = 0.106$, $\eta p^2 = 0.54$) in the control condition.



Note: * significant difference from baseline (p<0.05), n=10 for Creatine Kinase

Figure 4-2. Recovery time-course of indirect markers of muscle damage (mean ± 95% CI's) following downhill running (n = 12).



Note: * significant difference from baseline (p<0.05); Error bars omitted from control balance data to aid clarity of interpretation: Range of movement measured at the ankle joint; Control (n=4)

Figure 4-3. Recovery time-course of functional performance outcomes (mean ± 95% CI's) following downhill running (n = 12

Table 4-2. Mean difference from pre-exercise (Δ), 95% confidence intervals and effect sizes (*d*) for indirect markers of muscle damage, functional performance outcomes and readiness to exercise up to 96 h post downhill running (n = 12).

	Force Loss (N)	Creatine Kinase ($U.L^{-1}$)	Muscle Soreness (mm)	Balance (%)	Reactive Strength Ratio	Range of Movement (°)	Readiness to Exercise –0 - 6)							
							PPC	**MPC**	**EB**	**OR**	**MS**	**LOA**	**NES**	**OS**
Δ 24 h	-105.1*	257*	21.5*	-3.5*	-0.23*	-2.2	-1.58*	-0.67	-0.25	-2.17*	2.92*	0.92	0.17	1.33*
	(-204.9, -5.3)	(104, 410)	(1.2, 41.8)	(-6.8, -0.2)	(-0.32, 0.13)	(-5.2, 0.9)	(-2.98, -0.19)	(-1.98, 0.65)	(-1.55, 1.05)	(-3.52, -0.82)	(1.02, 4.82)	(-0.41, 2.24)	(-2.02, 2.35)	(0.02, 2.65)
	0.52	**2.48**	**1.46**	**0.54**	**0.53**	**0.35**	**1.04**	**0.62**	**0.23**	**1.41**	**1.77**	**0.60**	**0.10**	**0.95**
Δ 48 h	-102.2	92*	15.4	-1.6	-0.13	-0.7	-1.25	-0.42	-0.42	-1.58*	1.58	0.75	-0.08	0.75
	(-251.2, 46.9)	(23, 162)	(-2.1, 33.0)	(-5.1, 1.9)	(-0.24, 0.05)	(-4.45, 3.12)	(2.75, 0.25)	(-1.42, 0.59)	(-1.87, 1.04)	(-2.84, -0.33)	(-0.53, 3.22)	(-0.75, 2.25)	(-2.17, 2.00)	(-0.32, 1.82)
	0.50	**1.67**	**1.22**	**0.25**	**0.28**	**0.10**	**0.75**	**0.40**	**0.34**	**0.96**	**0.87**	**0.54**	**0.06**	**0.62**
Δ 72 h	-76.1	2.0	2.2	0.8	-0.11	0.3	-0.08	-0.08	0.00	-0.17	0.50	-0.08	-0.17	0.33
	(-188.1, 36.0)	(-33, 37)	(-6.3, 10.6)	(-1.5, 3.0)	(-0.27, 0.05)	(-2.98, 3.65)	(-1.09, 0.92)	(-0.99, 0.83)	(-0.86, 0.86)	(-1.21, 0.87)	(-1.35, 2.35)	(-1.34, 1.17)	(-1.98, 1.65)	(-0.91, 1.58)
	0.39	**0.03**	**-0.34**	**0.14**	**0.24**	**0.05**	**0.07**	**0.10**	**0.00**	**0.15**	**0.37**	**0.07**	**0.12**	**0.28**
Δ 96 h	-55.5	-1.0	-1.7	2.6*	-0.05	1.6	0.75	0.5	0.67	0.50	-0.50	-0.67	-0.92	0.50
	(-206.6, 94.9)	(-56, 53)	(-8.2, 4.8)	(-0.1, 5.3)	(-0.17, 0.08)	(-0.94, 4.11)	(-0.32, 1.82)	(-0.31, 1.31)	(-0.50, 1.83)	(-0.41, 1.41)	(-1.83, 0.83)	(-1.75, 0.42)	(-2.86, 1.03)	(-1.70, 0.70)
	0.26	**0.03**	**0.36**	**0.52**	**0.11**	**0.25**	**-0.73**	**-0.75**	**-0.77**	**-0.47**	**0.39**	**0.66**	**0.72**	**0.52**

Note: Information in provided in each cell top to bottom is mean difference, (95% confidence intervals) & **effect sizes**; * denotes significant difference from pre-exercise ($p < 0.05$); n = 10 for Creatine Kinase; Range of Movement measured at the ankle joint; Readiness to Exercise assessed using subscales of the Short Recovery and Stress Scale (SRSS): Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS)

4.3.3. Readiness to Exercise

There was a main effect for time on physical performance capability ($F = 12.99$, $p = 0.001$, $\eta p^2 = 0.54$), mental performance capability ($F = 4.52$, $p = 0.004$, $\eta p^2 = 0.29$), emotional balance ($F = 3.42$, $p = 0.016$, $\eta p^2 = 0.24$), overall recovery ($F = 19.82$, $p = 0.001$, $\eta p^2 = 0.64$), muscular stress ($F = 16.41$, $p = 0.001$, $\eta p^2 = 0.60$), lack of activation ($F = 6.29$, $p = 0.003$, $\eta p^2 = 0.36$) and overall stress ($F = 8.65$, $p = 0.001$, $\eta p^2 = 0.44$) in the experimental condition (Figure 4-4). Post-hoc analysis (Table 4-2) revealed physical performance capability ($p = 0.022$) and overall recovery ($p = 0.002$) were reduced and muscular stress ($p = 0.002$) and overall stress ($p = 0.046$) increased compared to pre-exercise at 24 h; overall recovery remained reduced ($p = 0.010$) 48 h post exercise. There was no main effect for time on negative emotional state ($F = 1.95$, $p = 0.168$, $\eta p^2 = 0.15$) in the experimental condition. There was no main effect for time on all subscales on the SRSS, in the control condition.

4.3.4. Repeated Associations Between Outcomes

Repeated associations between indirect markers of muscle damage, functional performance and readiness to exercise outcomes are provided in Table 4-3.

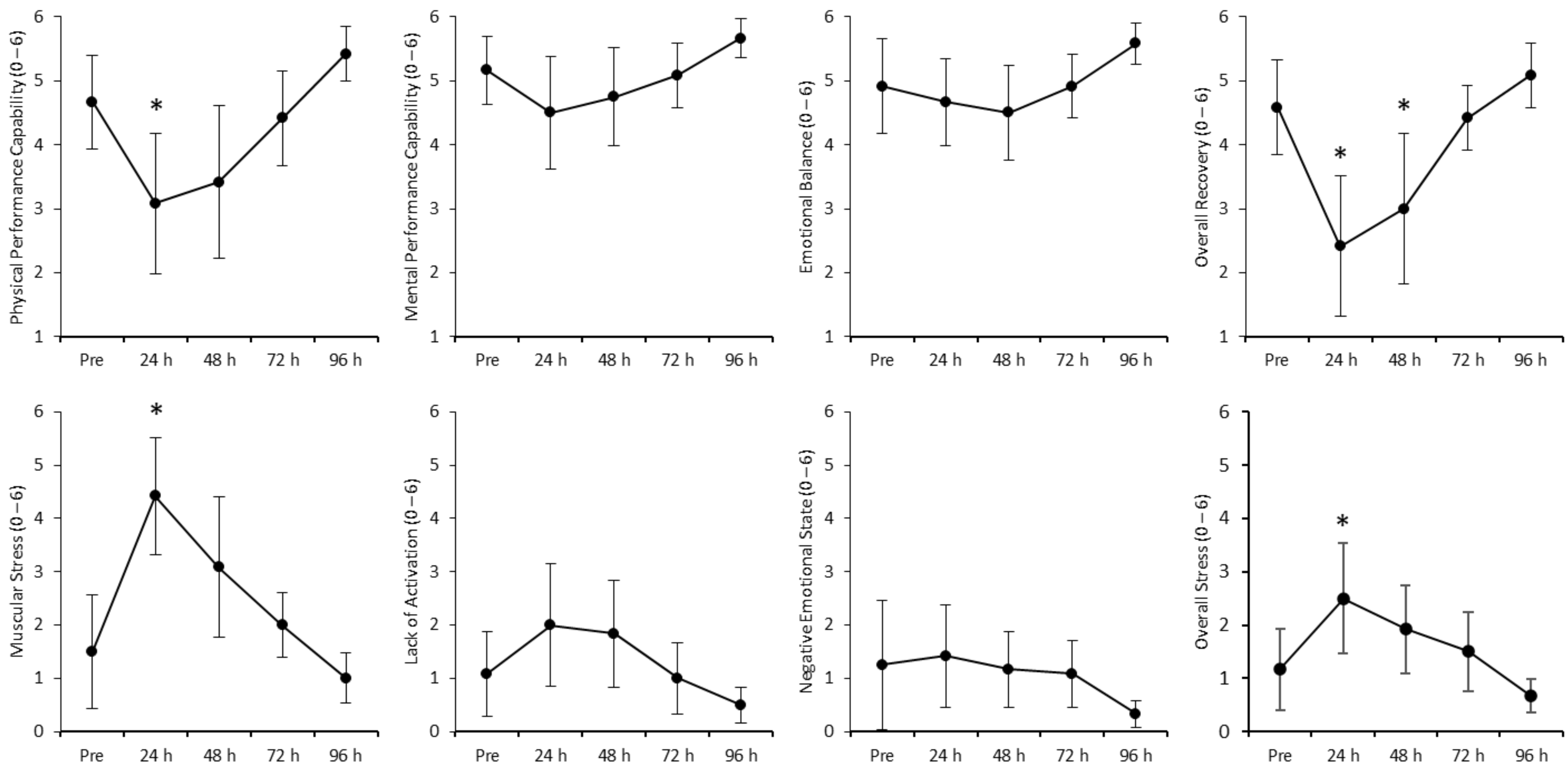


Figure 4-4. Recovery time-course of readiness to exercise (mean ± 95% CI's) following downhill running, assessed using subscales of the Short Recovery and Stress Scale (SRSS) (n = 12).

Table 4-3. Repeated measures correlation coefficients (RMCORR) for associations between common indirect markers of muscle damage, functional and psychological outcomes, following recovery from downhill running over 96 h (n = 12).

	Indirect Markers of Muscle Damage			Functional Performance			Readiness to Exercise							
	Force loss	**Muscle soreness**	**Creatine Kinase**	**Balance**	**Reactive Strength**	**Range of Movement**	**PPC**	**MPC**	**EB**	**MS**	**LOA**	**NES**	**OR**	**OS**
Force loss	-	**-0.34 [-0.57, -0.06]**	-0.25 [-0.52, 0.07]	**0.31 [0.03, 0.55]**	**0.47 [0.21, 0.67]**	**0.32 [0.04, 0.56]**	**0.41 [0.14, 0.63]**	**0.29 [0.01, 0.54]**	0.20 [-0.09, 0.46]	**-0.32 [-0.55, -0.03]**	-0.25 [-0.50, 0.04]	-0.17 [-0.44, 0.12]	**0.47 [0.21, 0.67]**	-0.25 [0.50, 0.04]
Muscle soreness	-	-	**0.63 [0.39, 0.79]**	**-0.78 [-0.87, -0.63]**	**-0.53 [-0.71, -0.28]**	**-0.50 [-0.69, -0.25]**	**-0.73 [-0.84, -0.56]**	**-0.54 [-0.71, -0.29]**	**-0.56 [-0.73, -0.33]**	**0.77 [0.63, 0.87]**	**0.69 [0.51, 0.82]**	0.21 [-0.09, 0.47]	**0.80 [-0.88, -0.66]**	**0.60 [0.38, 0.76]**
Creatine Kinase	-	-	-	**-0.55 [-0.74, -0.28]**	**-0.61 [-0.78, -0.36]**	**-0.47 [-0.68, -0.18]**	**-0.54 [-0.74, -0.28]**	**-0.46 [-0.68, -0.18]**	0.20 [-0.49, 0.12]	**0.66 [0.43, 0.81]**	**0.49 [0.20, 0.70]**	0.19 [-0.14, 0.47]	**-0.65 [0.80, -0.42]**	**0.46 [0.17, 0.68]**

Note: Significant ($p<0.05$) relationships in bold, [95% CI's], df = 47; n=9 for Creatine Kinase; Range of Movement measured at the ankle joint; Readiness to Exercise assessed using subscales of the Short Recovery and Stress Scale (SRSS): Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS)

4.4 Discussion

The aim of this research was to determine if functional and psychological outcomes are impaired following common muscle damaging exercise and consider their utility as proxy indicators of muscle damage. Indirect markers of muscle damage were largely affected 24-48 h post exercise, suggesting the DR had caused muscle damage. Balance ability and RS were impaired 24-48 h post exercise, with ROM remaining less affected. The DR increased feelings of stress and reduced feelings of recovery, suggesting individuals felt less ready to participate in exercise 24-48 h post muscle damaging exercise.

4.4.1. Indicators of Muscle Damage

Force production was impaired immediately post DR and the significant reduction remained 24 h post exercise. Additionally, muscle soreness and CK were significantly impaired to a large effect 24 h post exercise. The response observed in all three indirect markers of muscle damage suggests the DR successfully induced muscle damage. The observed responses in force loss, muscle soreness and CK are in line with those previously reported following DR (94, 111, 161, 175, 176, 180, 181, 183). A large to moderate effect was still evident for force loss, muscle soreness and CK 48 h post exercise, suggesting muscle damage was still evident at this time. At 72-96 h post exercise the effects had reduced suggesting muscle damage was now recovering.

4.4.2. Functional Outcomes

Balance ability and RS were significantly impaired following the DR, with the greatest reduction observed 24 h post exercise. The effect of these reductions was moderate, suggesting muscle damage was impairing functional ability. The reduction in balance of 3.5% could be impactful, with an imbalance of around 4% between limbs previously associated with a 2.5-4 times greater risk for injury (142, 188). Therefore, if individuals were to exercise 24 h post DR they may be at increased risk for injury. The observed balance reduction was smaller than previously reported (-9%) following repeated sprint muscle damaging exercise (16). However, this sprint activity resulted in a greater muscle damage response (as evidenced by force loss) compared to in the current investigation, which would explain a greater impact upon balance ability. Interestingly, 96 h post DR a moderate increase was observed in balance ability (+2.6%). Control condition data also showed a significant increase in balance ability at 72 h (+2.3%). This is unexpected as the balance test was conducted as previously suggested to avoid any learning effect occurring (145). This suggests that if the balance test is conducted repeatedly in a short time frame (each day over a week), that a learning effect may be evident, improving balance ability. This may have implications for the use of the balance test as a recovery tool and requires further investigation. The observed reduction in balance post DR may have been greater, as the learning effect may mask some of the impairment due to muscle damage.

The impairment in RS at 24 h supports the responses observed previously following sprint and dance muscle damaging activities (15). Therefore, RS may provide another tool which can indicate if muscle damage is present following exercise and can be assessed easily in the field requiring only lower cost equipment. RS was impaired to a greater extent in current study (13%) compared to the repeated sprint (8%) and dance specific (10%) investigations (15). This may be due to the DR causing more muscle damage than the sprint and dance activities, as suggested by the greater reduction observed in force loss.

There was less of an effect evident on ROM post completing the DR compared to the other functional outcomes (balance / RS), with a small to moderate reduction observed 24 h post exercise. It was expected a similar impairment would be observed in ROM as in previous investigations, as we observed similar impairments in both balance ability and RS (16, 115). However, both repeated sprint studies measured ROM at the knee, compared to the ankle location used in this investigation. Taken together, these findings suggest DR which results in muscle damage, leads to impairments in ROM of the knee but not the ankle (16, 115).

The time-course observed in the response of all functional performance outcomes was similar, with a peak reduction occurring at 24 h, reducing in effect at 48 h and then returning to near pre-exercise at 72-96 h. This response follows the same time-course observed in the indirect markers of muscle damage as indicated by a significant relationship over time between all the indirect markers of muscle damage and all measures of functional performance. This adds to current literature which has supported using functional outcomes to monitor recovery from muscle damaging activities (14-16, 27, 82, 83, 118). Functional measures may therefore provide alternative indicators of muscle damage, which are more related to sport / exercise performance and practically usable by both athlete and general public. Interestingly, the functional measures have a weaker association with the “gold standard” indicator for muscle damage (force loss) compared to muscle soreness and CK. The functional outcomes have the greatest association with muscle soreness, which may suggest they are more closely related to the mechanisms which lead to soreness occurring. This is understandable as the sensation of sore muscles may limit an individual's desire and subsequent ability to complete a functional movement assessment, which requires multiple muscles to work over a large ROM. Whereas, completing an isometric contraction to assess force is completed while seated statically, requiring the use of fewer muscles working over a smaller ROM, which is unlikely to result in as great as sensation of pain compared to the functional tests.

4.4.3. Readiness to Exercise

There has been limited research investigating how muscle damaging exercise may affect an individual's ability to complete further exercise. One day (24 h) post DR, individuals reported significantly reduced overall recovery and increased overall stress, with a very large effect. At 48 h a large to moderate detrimental effect still remained evident. Muscular stress (MS) demonstrated the greatest effect on the SRSS, being significantly impaired 24 h post exercise and still impaired to a very large effect at 48 h. A very large effect was also observed for physical performance capability (PPC), which was significantly impaired 24 h post exercise, remaining very largely impaired at 48 h. This suggests 24-48 h post exercise, individuals were feeling exhausted, fatigued, sore, stiff, less physically / mentally recovered, less relaxed, less physically capable and less energetic (154). Responses on these subscales seems intuitive as they are more directly linked to physical or functional outcomes. Similarly the Profile of Mood States (POMS) questionnaire, which has been used extensively with athletic populations, has identified changes on specific mood states (i.e., fatigue), in over trained athletes (194).

No statistically significant effect was observed on the SRSS for mental performance capability (MPC), lack of activation (LOA), emotional balance (EB) or negative emotional state (NES). However, LOA still appeared impaired to a large effect at both 24 and 48 h post exercise. This suggests individuals were feeling unmotivated, sluggish and had a lack of energy, which may be expected as muscle damage and functional impairment was present (195). There was a moderate effect on MPC 24 h post exercise and only a small effect was observed on EB and NES. These items appear less affected by muscle damaging exercise, which may be expected due to how they are more related to moods and emotions. Considering the large increase in how stressed and large decrease in how recovered individuals felt 24-48 h post DR, it appears individuals felt less ready to exercise at this time. Therefore, the SRSS provides an instrument which appears able to detect reduced readiness to exercise following muscle damaging exercise.

Additionally, using the simple 8-item SRSS assessment is relatively quick and easy to administer compared to some conventional indirect indicators of muscle damage (i.e., force loss, CK). This rapid assessment could be beneficial in many sport / exercise settings when looking to assess and monitor recovery from activities which may cause muscle damage. The assessment of muscle soreness using a VAS is equally quick to administer (132, 133). However, the readiness assessment may provide additional meaningful information about the overall recovery and stress state of the individual, that is not captured by a soreness value alone (155). The assessment of muscle soreness requires individuals to perform a muscle contraction as the sensation of pain is not felt while the muscle is static (134). This could lead to inaccuracies when completed by individuals alone, if they do not conduct this appropriately. The SRSS does not require any muscle contraction to be completed, which may lead to increased accuracy when complete by individuals repeatedly to assess their own recovery. The ability to detect readiness to exercise may assist in ensuring individuals receive adequate recovery, reduce the risk of injury and subsequently increase adherence to exercise. Further research is warranted to add support to the use of self-reported readiness to exercise as a measure for detecting and monitoring recovery from muscle damaging activities.

As observed for functional outcomes, there was also a significant association over time between the response observed in readiness to exercise and indirect markers of muscle damage (force loss, CK, muscle soreness). This was evident across the subscales of the SRSS closely related to physical and functional outcomes (PPC, MS, OR & OS), which as discussed represent the scales where an impairment was evident after completing the DR. Similarly, as observed with functional outcomes, the associations were greater between the readiness subscales and muscle soreness compared to the other indirect indicators of muscle damage. This is understandable as the sensation of sore muscles is likely to influence the response individuals report on these subscales of the SRSS. For example, a large association was observed between MS and muscle soreness, with the subscale requiring individuals to rate their "muscular stress" (e.g., muscle exhaustion, muscle fatigue, muscle soreness, muscle stiffness). Therefore, how individuals self-report readiness to exercise using the SRSS following muscle damaging exercise, may closely reflect the response observed for muscle soreness.

Interestingly the response of the indirect markers of muscle damage, functional performance outcomes and readiness to exercise appear to occur over similar time-course. The greatest impairments are observed 24 h post exercise, with some effects remaining impaired at 48 h, before all measures return to near pre-exercise levels at

72–96 h. The response in both the functional and psychological outcomes is significantly associated with the response observed in the indirect "gold standard" markers of muscle damage. Therefore, functional assessments and readiness to exercise outcomes may provide additional indicators of muscle damage which may be more accessible to individuals in regular sport and exercise settings compared to conventional indirect markers (e.g., force loss, myofibrillar proteins).

It is acknowledged that currently the functional assessments administered in this research require specific equipment and/or an individual to administer the test. However, these are more accessible and affordable than conventional laboratory assessments, such as force loss, assessed using an isokinetic dynamometer. Additionally, the field of athletic monitoring is advancing, with a smartphone/tablet app, now shown to be a valid and reliable assessment for jumping metrics (including RS) (196, 197). The findings of the current research along with those within the literature, suggest functional outcomes of balance and reactive strength are now being identified as indicators of muscle damage and recovery (15, 16, 27). Further work could seek to produce and refine modes to assess these metrics, which would further enhance their utility in monitoring in day-to-day sport and exercise settings. When used in combination these may provide a more complete and holistic approach to identifying EIMD and provide greater utility in informing total recovery and reducing the risk of overall injury, when completing further exercise. Additional research is required to determine how these outcomes respond to additional modes of exercise, to provide greater insight into how they can be used to monitor recovery from exercise.

4.4.4. Conclusions

In summary DR was effective at causing muscle damage, present for 24-48 h post exercise. Impairments were also evident in functional capability and readiness to exercise over the same time period and these were associated with the conventional indicators of muscle damage. Therefore, it may be possible to use these functional and psychological measures, to identify exercise which has resulted in muscle damage. These assessments may be more easily used to monitor ongoing recovery out in real world sport and exercise settings. Using functional and self-reported assessments in conjunction may provide a more holistic approach to monitoring recovery. Further research is required to understand how these measures respond following other activities, representative of those being undertaken in day-to-day life. This could change how muscle damage is monitored, assisting in understanding the recovery needs of individuals and facilitating adherence to further sport and exercise.

5. Muscle Damage and Recovery Following a Simulated Exercise Class

5.1 Introduction

As discussed previously (section 1.1), it is well established that performing unaccustomed exercise results in muscle damage, particularly when the exercise involves a large eccentric component. This was evidenced in (section 4) where a conventional laboratory mode of exercise, DR, resulted in muscle damage. Additionally, the DR resulted in impaired functional ability (balance and RS) and reduced readiness to exercise. Functional and readiness outcomes were related to the responses observed in indirect markers of muscle damage. This provided additional support to the current literature, where functional outcomes have been shown to be proxy indicators for muscle damage (14-16, 27, 82, 83, 118). These outcomes may provide indices of muscle damage that can be more readily assessed outside of laboratory settings. As discussed (section 1.6.2), functional outcomes such as balance and RS, provide practitioners with low tech and low-cost alternatives which better replicate the physical demands of sport while also being associated with performance and risk for injury (21, 120, 121). Therefore, using functional and readiness outcomes to assess muscle damage, is more likely to be accessible to those in conventional sport and exercise settings compared to conventional indirect indicators of damage.

As highlighted in section 1.4, in recent years there has been a shift within the literature to investigating the muscle damage response following activities which are more representative of those undertaken in day-to-day sport and exercise settings. The activities attempt to replicate the demands of sporting environments, which may be less severe and varied than those induced using common laboratory-based muscle damaging exercise protocols. As discussed (section 1.5.1), repeat sprinting, intermittent running and simulated rugby / dance exercise has been shown to result in prolonged force loss (15, 16, 27, 97, 99). Muscle soreness (section 1.5.2) was shown to be elevated in the days following repeat sprint, dance, basketball and football activities (15, 16, 27, 28, 99, 100, 105). CK has also been shown to increase (section 1.5.3) following repeated sprint, intermittent running, dance and simulated team sport protocols (16, 28, 99-103). The observed changes in these indirect markers of muscle damage, indicate that these sporting activities appear to cause muscle damage. However, a number of these investigations have utilised exercise protocols which are biased towards eccentric muscle actions. Multiple investigations have used repeated sprints with a rapid deceleration phase, leading to loading of the muscle as it acts eccentrically (15, 16, 27, 97-100, 115). It is likely this eccentric activity contributes heavily to the observed muscle damage and the exercise may not reflect the activity as it would be completed in the sporting world. Therefore, it is important for research protocols to accurately replicate how activity is conducted under “real world” conditions, to ensure the muscle damage response truly reflects the demands of the sport / exercise activity.

As discussed (section 1.4), a small number of investigations have even looked to investigate muscle damage following real-world sporting events (football, rugby, marathon, half-ironman) (106-109). However, utilising real sporting events is challenging, as outside of a laboratory environment conventional indirect markers of muscle damage can be difficult to obtain. Following elite level rugby matches muscle soreness and CK levels were reported to be increased up to 36 h post exercise (107). Marathon runners reported muscle soreness when measured post event, however, no pre-race measurements were obtained (108). Myofibrillar proteins were also found to be increased following a football match; no further measurement times were included to further monitor the time-course of this response (106). Currently it appears no research has investigated force loss following real world sporting events, which would be very informative when looking to understand the muscle damage response as it is considered the “gold standard” indirect assessment (13). The lack of consistent measurement time points, including pre-exercise assessments, assessed at repeated time points, limits the ability to understand the muscle damage response following these sporting events. Research should replicate these sports and others under simulated settings, to allow for appropriate assessments to be measured at repeated time points, thereby providing more insight into how these activities may result in muscle damage.

Currently all the research which has investigated the muscle damage response following “real world” activities has been focused on modes of exercise which are primarily concerned with competitive sport. Individuals across the country regularly conduct exercise activities in their day-to-day life. Fitness classes are a popular mode of exercise and it was estimated around 6 million adults in the UK regularly take part in this type of activity based on data from the recent Sport England survey (Active Lives) (198). Additionally, fitness classes represent the second most completed type of exercise activity in the UK between 2019-20 (199). Therefore, understanding how fitness classes may cause muscle damage and the subsequent recovery is of great interest to understand the needs of individuals who regularly complete these activities. Currently, no research has considered how these types of exercise activities may result in muscle damage. The exercises can be completed using only the resistance of bodyweight and contain large compound exercise movements, containing both eccentric and concentric phases of muscle action. As discussed (section 1.4), large multi joint and / or muscle exercise protocols (DR, plyometric jumps, squats) have been shown to result in muscle damage (82, 111). During fitness classes plyometric exercises are often completed in an explosive manner, requiring the rapid transition from a concentric to eccentric muscle contraction (i.e., completing a squat jump) (200). Therefore, it may be expected that completing a fitness class which contains large movements, working multiple muscle groups, rapidly changing from concentric to eccentric phases of muscle actions may result in muscle damage. As discussed (section 0), RS is vital for activities containing a fast stretch shortening cycle, where an individual explosively transitions between concentric and eccentric phases of muscle action. Understanding how RS may be impaired following an EC would provide insight into if individuals should be conducting further explosive exercise movements in the subsequent days post exercise. In the previous chapter (section 4.3.2) DR was shown to impair balance ability and RS over a similar time course. Therefore, understanding how balance ability may also be impaired following EC activities would offer further insight into how individuals may be at increased risk of injury in the days following exercise. As discussed, reduced balance ability has been associated with an increased risk of injury. Therefore, if completing an EC reduces balance ability, individuals may need to avoid certain exercise activities or allow for adequate recovery in the days immediately post exercise., to avoid the risk of injury.

In section 4.3.4, the response of functional and self-reported readiness to exercise outcomes were found to be associated with the response of indirect makers of muscle damage. This may suggest that functional and readiness outcomes, which can be accessed more readily outside of laboratory environments, may provide proxy indicators for muscle damage. However, this was observed following a conventional laboratory mode of exercise known to result in muscle damage. More research is required to investigate if these associations are present following regular modes of exercise. Understanding how these outcomes may be associated after EC activities, would provide insight into how proxy indicators for muscle damage may be used to monitor recovery following “real world” exercise activities.

5.1.1. Aims & Research Questions

The purpose of this experimental chapter is to determine if completing an EC, which is representative of activity currently being undertaken within the United Kingdom and worldwide, results in muscle damage. Additionally, the response of functional and self-reported readiness to exercise outcomes will be investigated. Finally, the association between indirect makers of muscle damage and functional and readiness outcomes will be investigated, to determine how these may provide proxy indicators for muscle damage. The investigation will answer the following research questions:

1) Does completing a bodyweight EC result in muscle damage?
2) Are functional outcomes affected following a bodyweight EC?
3) Is readiness to exercise affected following a bodyweight EC?
4) Is the response of functional and readiness outcomes following a bodyweight EC associated with the response observed in indirect markers of muscle damage?

5.2 Materials and Methods

5.2.1. Participants

Participants were 15 (9 male) healthy, recreationally active adult volunteers, who reported taking part in structured exercise two-five times per week (Table 5-1). Participants regularly completed common exercise activities (e.g., resistance training, aerobic exercise, team sports), however, they not been involved in completing explosive whole body exercise movements within the last six months. Prior to commencing participation participants were screened for contraindicators to exercise using the PAR-Q (Appendix H). As described (section 2.1), ethical approval to perform the research was granted by the University of Essex ethics committee and written informed consent was provided by all participants, prior to commencing experimental work.

Table 5-1. **Participant characteristics (n = 15).**

Age (years)	Stature (m)	Mass (kg)	Body Mass Index ($Kg.m^2$)
33.6 ± 10.4	1.72 ± 0.09	72.6 ± 12.4	24.5 ± 3.6

Note: Females (n = 6)

5.2.2. Procedures

All participants attended the laboratory in the week prior to completing the simulated EC to be familiarised with all outcome measures. In the following week

(Figure 5-1) participants attended the laboratory (Visit 1) to complete pre-exercise measurements conducted in the following order: 1) SRSS 2) CK 3) MVIC & Muscle Soreness 4) RS 5) Balance. Following pre-exercise measurements participants completed the simulated EC; immediately post exercise another MVIC measurement was conducted. Participants attended the laboratory at 24 h (Visit 2), 48 h (Visit 3), 72 h (Visit 4) and 96 h (Visit 5) post Visit 1, for repeat testing of all outcomes conducted in the same order as at pre-exercise. Participants completed an initial warm-up at each visit following the measurement of CK, comprising of ten bodyweight squats and ten bodyweight lunges, at a low intensity. The laboratory was kept at a consistent temperature (20 °C) and participants attended at the same time of day (± 1 h) across all visits, to minimise the influence of circadian rhythm on performance (184, 185). Participants were requested to refrain from completing structured exercise activities while participating in the research.

i. Simulated Exercise Class

Participants completed a Les Mills Grit Cardio™ workout in the laboratory with instructional guidance displayed on a large screen. The Les Mills Grit series is a high intensity workout comprised of strength and plyometric exercise (201). The workout duration was approximately 30 min and included a structured warmup (Appendix J). No equipment was required with all movements using bodyweight for resistance. If individuals were unable to perform the required full movement a scaled alternative was provided. Individuals were requested to complete as much exercise as they were able and verbal encouragement was provided throughout.

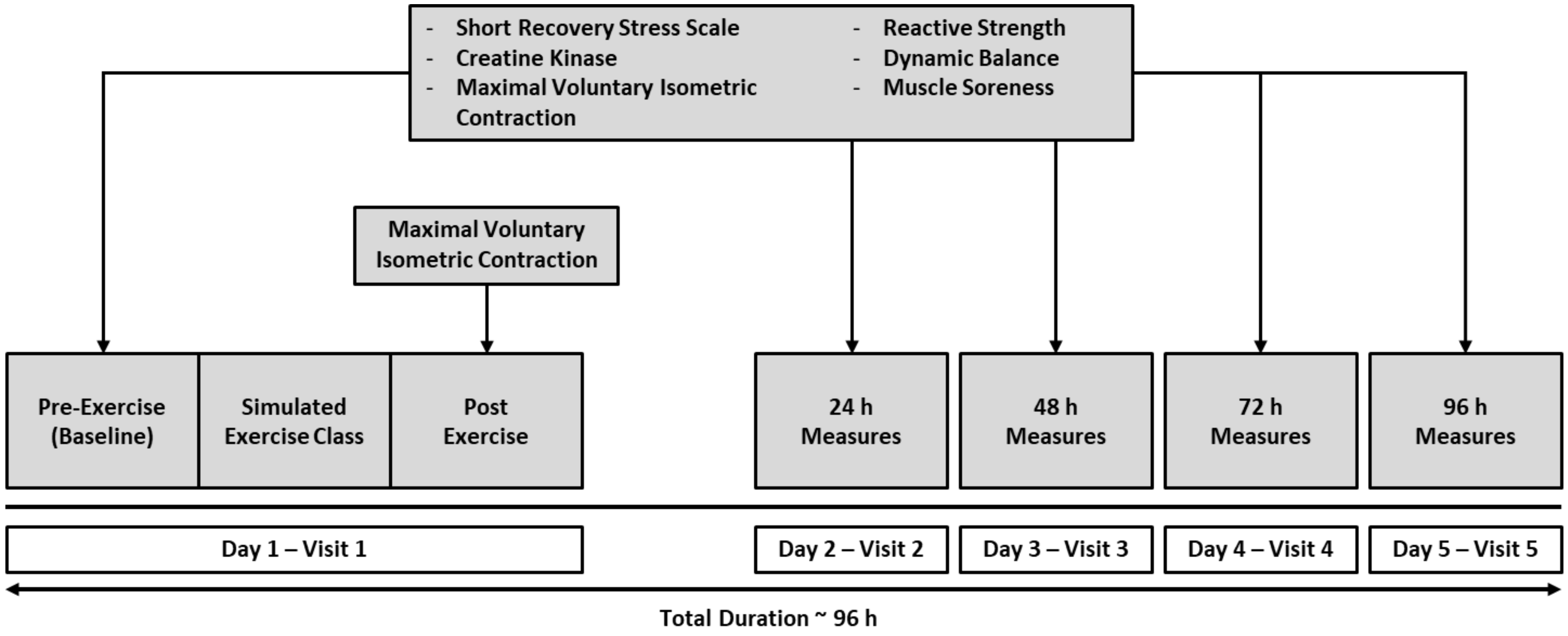


Figure 5-1. **Schematic representation of the experimental protocol used to conduct a simulated exercise class and monitor recovery up to 96 h post exercise.**

5.2.3. Measures

i. Force Loss

Force loss was measured using MVIC's as previously described in section 2.2.1.

ii. Muscle Soreness

Muscle soreness was assessed using a VAS as previously described in section 2.2.2. Muscle soreness ratings were assessed by participants rating the pain or discomfort they perceived when completing the MVIC.

iii. Creatine Kinase

Creatine Kinase assays were conducted from venous blood samples as previously described. CK was not assessed for five participants, as they did not wish to have venous blood samples taken; two additional participants had their CK measures excluded as the external laboratory reported these samples were not suitable for analysis.

In section 2.2.3.

iv. Balance

Balance was assessed using the Y-Balance test as previously described in section 2.2.4.

v. Reactive Strength

RS was determined using the RSR from DJs as previously described in section 2.2.5.

vi. Readiness to Exercise

Self-reported readiness to exercise was measured using the SRSS as previously described in section 2.2.6.

vii. Heart Rate

Heart rate was assessed to monitor exercise intensity as previously described in section 2.2.8. Percentage of age-predicted HR max was calculated as previously suggested: $HR_{max} = 206 – 0.7 \times age$ (202).

5.2.4. Statistical Analysis

An a priori power analysis was conducted as described (section 0) to determine significant power using a large effect size (*f =0.4)*, revealing a required sample size of 13 participants per condition. Two-way ANOVA (2 x 5) were used as previously described (section 0) to determine there was no effect of sex on all outcomes. Male and female participants were then grouped together for all subsequent analysis. A paired samples t-test was used to determine differences between MVIC at pre-exercise and immediately post exercise. One-way ANOVA (1 x 5) were used to determine the effect of time on all outcomes as previously described (section 0). Effect sizes from ANOVA were reported as partial Eta squared (ηp^2) (191). RMCORR were used to determine repeated associations between indirect markers of muscle damage and functional and readiness to exercise outcomes, as described in section 0. Mean ± 95% confidence interval statistics were calculated and presented in figures (Microsoft Excel, Microsoft Office 365 Pro Plus). Mean difference from pre-exercise, effect sizes *(g)* and correlation coefficients with 95% CI's were calculated and presented in tables (192, 193). Missing data cases were imputed as described previously (section 2.3.1) due to satisfying the condition that they were missing at random; values were imputed for one participant across all outcomes at one time point (96 h), as they did not present at one testing visit (Visit 5). Descriptive statistics for all measures, at all-time points, are provided in Appendix K.

5.3 Results

5.3.1. Force Loss

Force was reduced ($t = 2.96$, $p = 0.010$, $g = 0.33$) immediately post exercise (639 ± 250 N) compared to pre-exercise (725 ± 254 N). There was no main effect of time for force ($F = 0.82$, $p = 0.518$, $\eta p^2 = 0.06$; Figure 5-2).

5.3.2. Muscle soreness

There was a main effect of time for muscle soreness ($F = 9.45$, $p = 0.001$, $\eta p^2 = 0.40$; Figure 5-2); post-hoc analysis revealed soreness was increased ($p = 0.015$) at 24 h compared to pre-exercise (Table 5-2).

5.3.3. Creatine Kinase

There was a main effect of time for CK ($F = 4.90$, $p = 0.004$, $\eta p^2 = 0.41$; Figure 5-2), with no significant difference compared to pre-exercise at any individual measurement time point (Table 5-2).

5.3.4. Balance

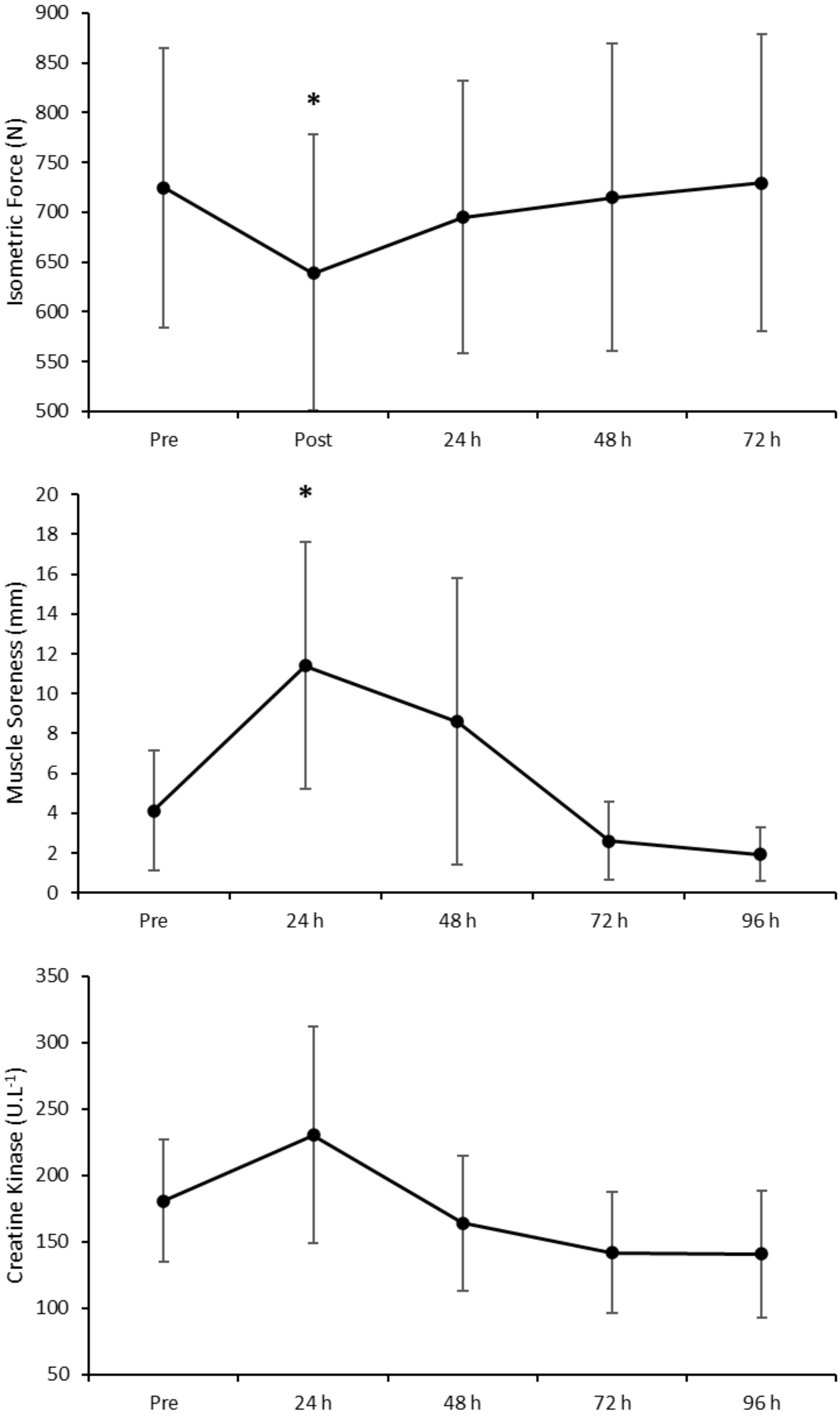
There was a main effect of time for balance ($F = 11.76$, $p = 0.001$, $\eta p^2 = 0.46$; Figure 5-3); post-hoc analysis revealed balance was increased at 72 ($p = 0.033$) and 96 h ($p = 0.008$) compared to pre-exercise (Table 5-2).

5.3.5. Reactive Strength

There was a main effect of time for RS ($F = 4.16$, $p = 0.005$, $\eta p^2 = 0.30$; Figure 5-3): post-hoc analysis revealed RS was reduced at 72 ($p = 0.045$) and 96 h ($p = 0.002$) compared to pre-exercise (Table 5-2).

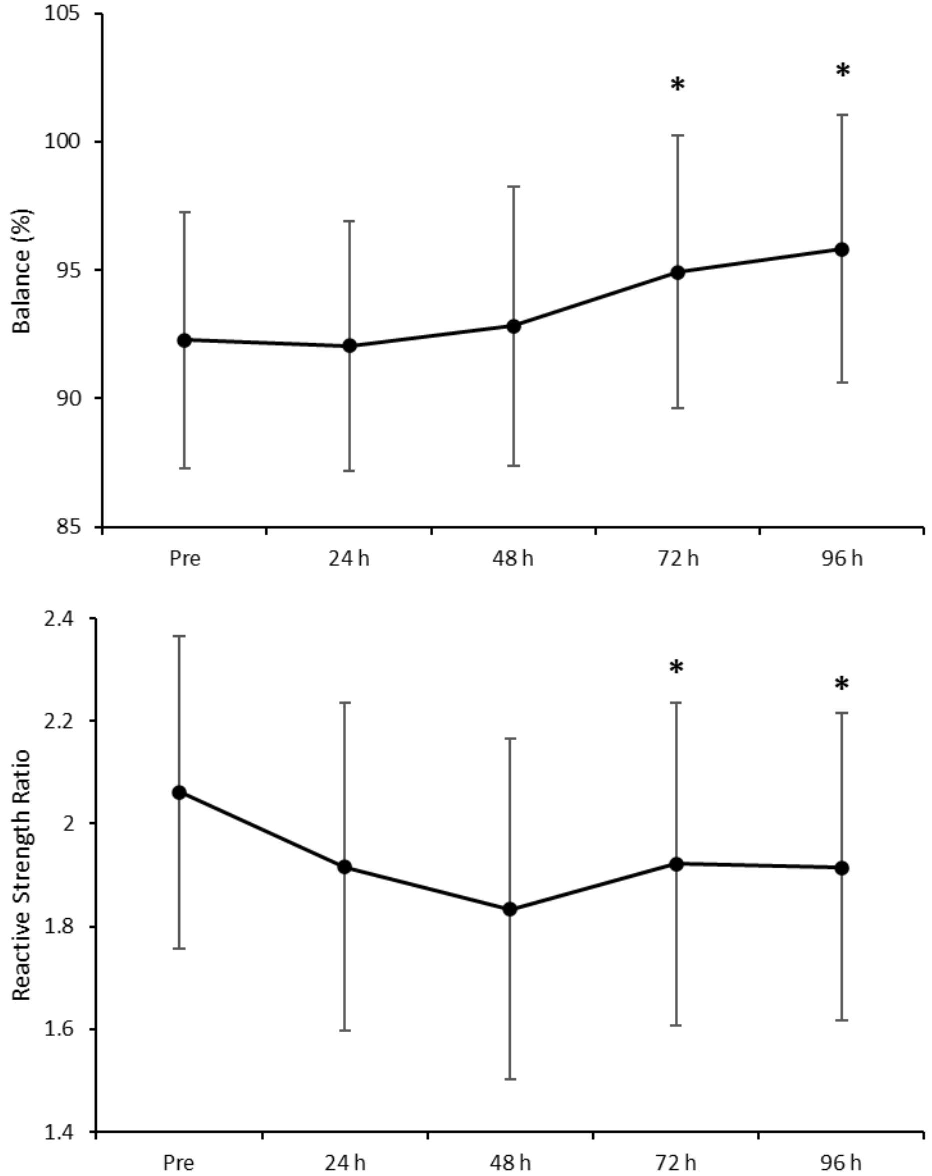
5.3.6. Readiness to Exercise

There was a main effect of time (Figure 5-4) for PPC ($F = 9.67$, $p = 0.001$, $\eta p^2 = 0.41$), MPC ($F = 2.72$, $p = 0.038$, $\eta p^2 = 0.16$), OR ($F = 21.68$, $p = 0.001$, $\eta p^2 = 0.61$), MS ($F = 25.45$, $p = 0.001$, $\eta p^2 = 0.65$) and OS ($F = p = 0.10$, $\eta p^2 = 0.21$). Post-hoc analysis (Table 5-2) revealed at 24 h post exercise OR was reduced ($p = 0.009$) and MS increased ($p = 0.002$) compared to pre-exercise. At 48 h post exercise MS was increased ($p = 0.046$) compared to pre-exercise. No main effect of time was evident for EB ($F = 2.49$, $p = 0.053$, $\eta p^2 = 0.15$), LOA ($F = 2.23$, $p = 0.077$, $\eta p^2 = 0.14$) or NES ($F = 1.46$, $p = 0.226$, $\eta p^2 = 0.09$).



Note: * significant difference from pre-exercise ($p < 0.05$), n=8 for Creatine Kinase

Figure 5-2. **Recovery time-course of indirect makers of muscle damage (mean ± 95% CI's) up to 96 h post completing a simulated exercise class (n = 15).**



Note: * significant difference from pre-exercise ($p < 0.05$)

Figure 5-3. **Recovery time-course of functional performance outcomes (mean ± 95% CI's) up to 96 h post completing a simulated exercise class (n = 15)**

Table 5-2. Mean difference from pre-exercise (Δ) and effect sizes (*g)* for indirect markers of muscle damage, functional performance and readiness to exercise up to 96 h post completing a simulated exercise class (n = 15).

	Force Loss (N)	**Creatine Kinase (U/l)**	**Muscle Soreness (mm)**	**Balance (%)**	**Reactive Strength Ratio**	**Readiness to Exercise (0 – 6)**							
						PPC	**MPC**	**EB**	**OR**	**MS**	**LOA**	**NES**	**OS**
Δ **24h**	-29.5 **0.11**	49.6 **0.59**	7.3* **0.80**	-0.22 **0.02**	-0.14 **0.25**	-0.6 **0.53**	0.1 **0.05**	-0.34 **0.27**	-1.27* **0.93**	2.27* **2.16**	0.40 **0.36**	0.34 **0.33**	0.80 **0.69**
Δ **48h**	-9.6 **0.04**	-16.9 **0.28**	4.5 **0.46**	0.55 **0.06**	-0.23* **0.39**	-0.6 **0.46**	0.1 **0.05**	-0.20 **0.16**	-0.80 **0.63**	1.27* **1.23**	0.40 **0.32**	0.07 **0.07**	0.60 **0.47**
Δ **72h**	5.0 **0.02**	-38.9 **0.68**	-1.5 **0.33**	2.63* **0.28**	-0.14* **0.24**	0.5 **0.52**	0.6* **0.56**	0.53 **0.46**	0.60 **0.52**	-0.07 **0.06**	-0.40 **0.39**	-0.26 **0.25**	-0.20 **0.20**
Δ **96h**	-4.1 **0.02**	-39.9 **0.69**	-2.2 **0.51**	3.54* **0.37**	-0.15* **0.26**	0.7 **0.60**	0.6 **0.54**	0.33 **0.24**	1.07 **0.91**	-1.00 **1.07**	-0.33 **0.24**	-0.33 **0.31**	-0.20 **0.19**

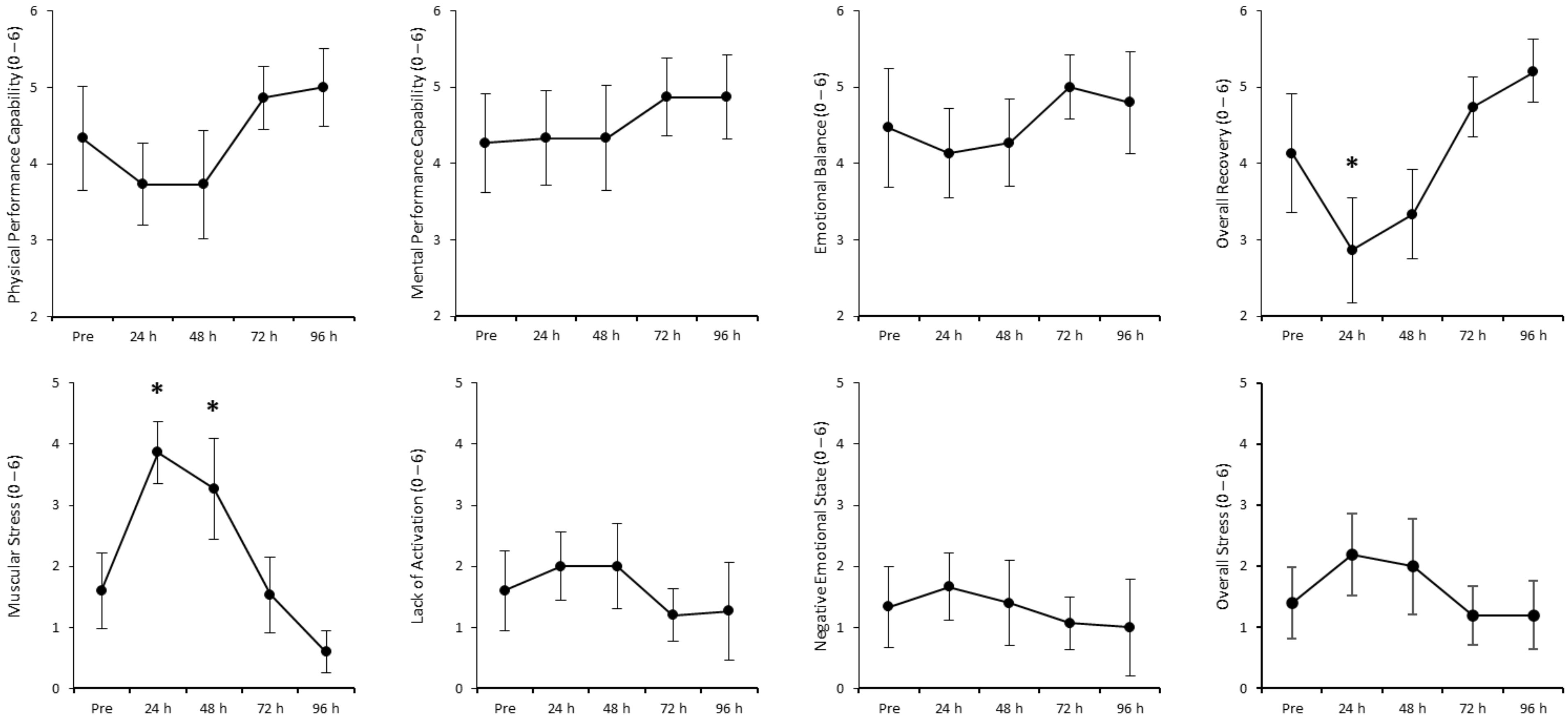
Note: * denotes significant difference from pre-exercise ($p < 0.05$); n=8 for Creatine Kinase; Readiness to Exercise assessed using subscales of the Short Recovery and Stress Scale (SRSS): Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS)

5.3.7. Repeated Associations with Indirect Markers of Muscle Damage

Repeated associations between indirect markers of muscle damage and functional performance and readiness to exercise outcomes are provided in Table 5-3.

5.3.8. Exercise Intensity

The mean intensity of exercise during the Grit Cardio workout was 151 ± 14 $b.min^{-1}$, which was equivalent to 83.4 ± 7.5 % of the age predicted maximum. (Figure 5-5).



Note: ***** denotes significant difference from pre-exercise (p<0.05)

Figure 5-4. **Readiness to exercise (mean ± 95% CI's) up to 96 h post completing a simulated exercise class, self-reported using the Short Recovery Stress Scale (SRSS) (n = 15).**

Table 5-3. Repeated measures correlation coefficients (RMCORR) for associations between indirect markers of muscle damage, functional performance and readiness to exercise outcomes, up to 96 h post a simulated exercise class (n = 15).

	Indirect Markers of Muscle Damage			Functional Performance		Readiness to Exercise							
	Force loss	Muscle soreness	Creatine Kinase	Balance	Reactive Strength	PPC	MPC	EB	OR	MS	LOA	NES	OS
Force loss	-	-0.19 [-0.42, 0.07]	**-0.38 [-0.65, -0.03]**	**-0.28 [0.03, 0.50]**	0.13 [-0.13, 0.37]	**0.27 [0.01, 0.49]**	**0.28 [0.03, 0.50]**	0.14 [-0.12, 0.39]	0.16 [-0.10, 0.40]	-0.13 [-0.38, 0.13]	-0.12 [-0.37, 0.14]	0.00 [-0.26, 0.26]	**-0.24 [-0.47, 0.01]**
Muscle soreness	-	-	0.33 [-0.03, 0.61]	**-0.45 [-0.63, -0.22]**	**-0.48 [-0.65, -0.25]**	**-0.56 [-0.71, -0.35]**	**-0.44 [-0.62, -0.20]**	**-0.34 [-0.55, -0.10]**	**-0.59 [-0.73, -0.39]**	**0.56 [0.35, 0.71]**	**0.31 [0.06, 0.53]**	**0.30 [0.05, 0.52]**	**0.38 [0.14, 0.58]**
Creatine Kinase	-	-	-	**-0.34 [-0.62, 0.01]**	-0.11 [-0.45, 0.25]	**-0.52 [-0.74, -0.20]**	**-0.47 [-0.07, -0.14]**	-0.30 [-0.59, 0.06]	-0.32 [-0.61, 0.03]	0.32 [-0.03, 0.61]	**0.59 [0.29, 0.78]**	0.31 [-0.05, 0.60]	**0.43 [0.09, 0.68]**

Note: Significant ($p<0.05$) relationships in **bold,** [95% CI's], n=8 for Creatine Kinase; Readiness to Exercise assessed using subscales of the Short Recovery and Stress Scale (SRSS): Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS); RMCORR conducted using pre-exercise and 24, 48, 72 & 96 h post exercise measurement time points.

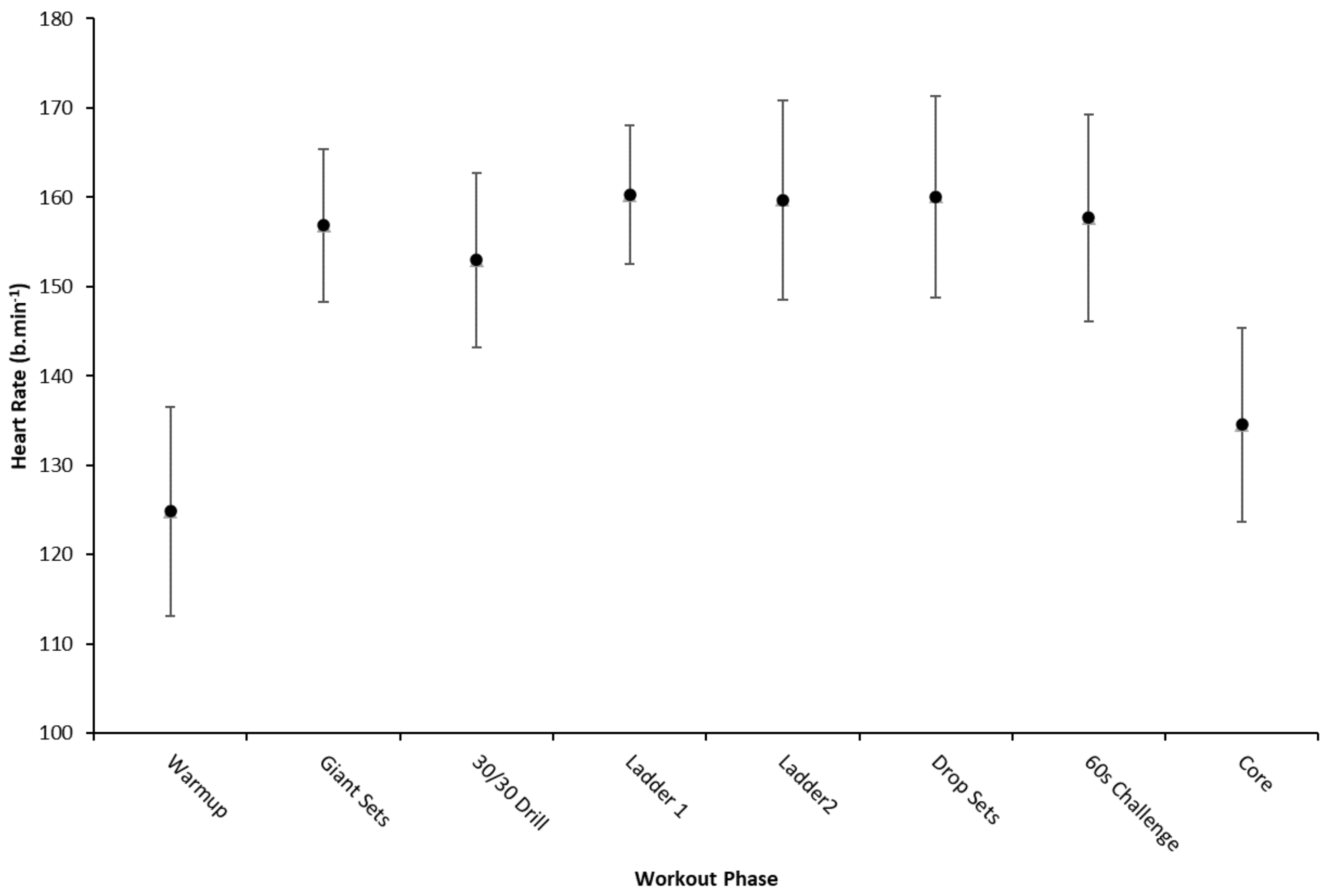


Figure 5-5. **Heart rate (mean ± 95% CI's) by workout phase during a simulated exercise class (n = 9).**

5.4 Discussion

5.4.1. Exercise Class Activities and Muscle Damage

The first aim of this investigation was to determine if completing a bodyweight EC results in muscle damage. Considering the response of the indirect markers of muscle damage, muscle soreness was the only indicator of damage to increase significantly, at 24 h post exercise. Force loss, which as discussed previously (section 1.5.1) is considered the “gold standard” indirect assessment for muscle damage, was only impaired immediately post exercise. However, this reduction (12%) which indicated the quadriceps had been fatigued, is smaller than that observed following DR (19%) in the previous chapter (section 4) where a larger effect was evident. The reduction was comparable to the sport specific investigations within the literature, where an 8-12% drop in force was observed following sprinting and dance activities (15, 16, 27).

At 24 h and subsequent time points there was little change in isometric force, suggesting muscle damage that results in force loss had not occurred. This is in contrast to the previous sport specific investigations where a significant decline in force generating ability remained evident 24 h post exercise (15, 97, 99). CK was only slightly elevated 24 h post the EC, to a small to moderate effect, supporting that minimal muscle damage had occurred. Additionally, the muscle soreness increase reported at 24 h was a much smaller effect than observed previously following DR (section 4.3.1). Therefore, it appears conducting the EC resulted in little to no muscle damage, with individuals only reporting some moderate increases in muscle soreness.

Interestingly, the EC was completed at a very high intensity (151 b.min^{-1}; 83% of HR max), which is greater than previously observed following DR which resulted in force loss (section 3.2.3.iii). Consequently, it would be expected the exercise intensity was sufficient to invoke a muscle damage response, as higher velocity contractions have been associated with increased muscle damage (36). These findings have implications for selection of recovery strategies and safe participation in EC activities. If no muscle damage occurs following an EC, recovery strategies selected based on the literature may not be appropriate. Historically, recovery research has investigated the effectiveness of therapeutic interventions following laboratory-based exercise which results in large amounts of muscle damage (29-33). More research is required to directly compare the muscle damage response following conventional muscle damaging exercise (e.g., DR) and EC activities. This would provide insight into how the muscle damage response is different between these activities, which has implications for subsequent recovery / therapeutic approaches.

5.4.2. Functional Responses Following Exercise Class Activities

The second aim of this investigation was to determine if functional (balance & RS) outcomes were impaired following bodyweight EC activities. Balance ability remained similar to pre-exercise 24-48 h post exercise, suggesting completing the EC did not impair balance. This is in contrast to following DR (section 4.3.2) where a reduction in balance ability was observed 24-48 h post exercise, when completing the same balance test. Research utilising repeated sprint exercise showed standing balance to be impaired in the days following exercise (16). However, both the DR and repeated sprinting activities resulted in muscle damage as evidenced by reduced force generating capacity, which may explain why balance ability was also impaired. This may indicate that muscle damage is required in the leg muscles, to impair balance performance on tests predominately completed using the lower limbs. Conversely, balance ability has been shown not to be impaired following split squat exercise, even when muscle damage was evidenced by reductions in force (81). It was suggested that the balance test assessed using the Biodex Balance System may not have been challenging enough to result in impaired balance in this instance. The Y-balance test used in the current investigation is more dynamic than the measures taken using the Biodex system and if balance was impaired, it would have been expected to be detected using this assessment. More research is needed to directly compare the recovery of balance between exercise which does (e.g., DR) and does not (e.g., EC activities) cause muscle damage. This would provide insight into how muscle damage and where it is located (i.e., lower limb), may impair balance performance. As discussed (section 4.4.2), reduced balance ability is associated with an increased risk of injury. Therefore, understanding how balance may be impaired post exercise has implications for the appropriate and safe selection of subsequent exercise activities.

A small to moderate significant increase was observed in balance ability 72-96 h post exercise. This supports the previous observations following DR (section 4.3.2) where an increase in balance compared to pre-exercise was observed 3-4 days post exercise. As discussed previously (section 4.4.2), it appears that repeatedly completing the balance test in short period of time (day to day), results in improved proficiency on the Y-balance balance test. This occurs even when practice trials are included, which has been suggested to avoid a learning effect (145). If a lower limb task specific learning effect is occurring, this may mask any balance declines which occur in response to exercise (i.e., completing an EC). Additionally, individuals are able to observe their performance on the test, as the measurement numbers are visible next to the reach indicator. The short time period (24 h) between visits would enable individuals to recall their previous scores and potentially motivate them to achieve or better previous attempts. In the research assessing the reliability of the balance test, a different version of the balance test was used, with no reach distance visible to the participants (145). This may explain why no learning effect was observed compared to this investigation and compared with the observations in the previous section (section 4). Research is required to investigate how the repeat day-to-day testing of the Y-balance test results in a learning effect and if this effect is evident if reach distance is not visible. This would provide vital insight which is needed to enable the Y-balance test to be used to regularly to assess recovery from exercise.

In contrast to balance ability, a moderate impairment was observed in RS 24-48 h post exercise and this remained until the final assessment 96 h post exercise. This supports previous observations following repeated sprinting and dance activity within the literature, where RS was shown to be impaired 24-48 h post exercise (15, 27). However, these activities also resulted in prolonged force loss and RS returned towards pre-exercise by 72 h post exercise. It is interesting in this instance that RS appears impaired up to 4 days post exercise even though no muscle damage appears to have been caused, as evidenced by force loss. Monitoring recovery from exercise using functional outcomes may have practical applications in detecting important impairments which would not be evident using conventional indirect assessments for muscle damage. The workout used in this investigation contained a large amount of plyometric jumping movements completed at a high intensity, requiring repeated stretch-shortening cycle muscle actions, which may explain why RS was impaired. Repeated explosive stretch-shortening actions during jumping in the EC would have affected the muscles required to complete the similar DJ movements, used to conduct the RS assessments. Isometric force was measured in the quadriceps following the EC, which may be less impacted by the explosive jumping movements. However, previous research evidenced both force and RS declines when assessments were taken isometrically in the quadriceps (27). Perhaps RS is more sensitive compared to conventional isometric assessments of force loss after completing a high volume of explosive jumping exercise actions. More research is required to further investigate the RS in response to explosive exercise activities and how this relates to force production across multiple lower limb muscle groups. This would provide further clarity into the use of RS when monitoring recovery from explosive exercise activities.

5.4.3. Readiness to Exercise Following Exercise Class Activities

The third aim of this investigation was to determine if readiness to exercise was affected following the bodyweight EC. From the eight subscales used to self-report readiness to exercise, an impairment was only evident across four subscales 24-48 h post exercise. PPC and OR were reduced, and MS and OS increased to a moderate to large effect, suggesting readiness to exercise was reduced. The subscales of MPC, EB, LOA and NES were less affected, which may be expected as these represent constructs of cognitive function and moods / emotions. A similar trend was observed in the previous chapter (section 4.3.3) following DR, where subscales which are associated with physical and overall constructs of stress and recovery were impaired. This may suggest that when acutely monitoring recovery from an individual bout of exercise with how individuals rate readiness to exercise, that the four “physical” and “overall” constructs are those most relevant. The SRSS was designed for monitoring the recovery-stress state of athletes and the scales related to moods / emotions may be more relevant for this purpose, as mood state changes are regarded as a symptom of burnout (203). A trend was observed across the readiness to exercise subscales where individuals reported themselves more recovered (increased recovery, reduced stress) at 96h than they had been when assessed pre-exercise. This trend was also apparent in the previous section (4.3.3) 96 h post completing DR. It is possible this is due to the final testing visit being completed at the end of a typical work week, on a Friday. More research is required to understand how external factors may influence how individuals report their readiness to exercise and how this impacts its use as tool for monitoring recovery from regular exercise activities.

Interestingly, readiness to exercise appears impaired following the EC without muscle damage (force loss) being evident. However, muscle soreness was increased post EC, which may indicate that if exercise results in increased muscle soreness, physical and overall components of readiness to exercise will also be affected. Compared to the previous investigation utilising DR (section 4.3.3), the magnitude of change observed in readiness to exercise was smaller following the EC. This may suggest that if exercise results in muscle damage it will have a greater effect on an individual’s readiness to exercise. Additionally, the DR resulted in a greater increase in muscle soreness compared to the current investigation. This may suggest the responses of readiness to exercise and muscle soreness are closely related. Research should directly compare the response of readiness to exercise following common muscle damaging exercise (e.g., DR) and EC activities. This would provide greater insight into the sensitivity of readiness to exercise assessments for monitoring recovery and what would constitute a meaningful change.

5.4.4. Associations Between Outcomes

The final aim of this investigation was to determine if the response observed in functional and readiness to exercise outcomes was associated with the response of indirect makers of muscle damage. Muscle soreness was the only indirect indicator of muscle damage that was consistently and significantly associated with the changes in functional and readiness outcomes over time, following the EC. In the previous investigation (section 4.3.4) following DR, it appeared functional and self-reported readiness outcomes may provide proxy indicators for muscle damage. The observed associations were greater and more consistently associated with all indirect markers of muscle damage following the DR compared to the responses observed after the EC. Across both investigations the associations were greater between muscle soreness and functional and readiness outcomes compared to the other conventional indicators of muscle damage. In the current investigations the associations were smaller than previously observed following the DR (moderate compared to large), which resulted in muscle damage (section 4.3). Functional and readiness outcomes may only be strongly associated with conventional indicators when muscle damage has occurred. These assessments may be more sensitive to change and only offer proxy indicators for muscle damage when a sufficiently meaningful change has occurred. Further research is required to determine the suitability of functional and readiness outcomes in providing proxy indicators for muscle damage which can be accessed in regular exercise environments.

A number of factors may contribute to the observed associations between muscle soreness and functional and readiness to exercise outcomes. Muscle soreness may impair an individual's ability to complete a functional test, as the sensation of pain is likely to impede an individual when completing a dynamic exercise movement. When self-reporting across the subscales of readiness exercise which appear impaired post exercise (e.g., PPC, OR, MS, OR), individuals are provided with examples of what each subscale represents (see Appendix G) such as: muscle soreness, physically exhausted, physically capable, muscle relaxation, recovered. When considering how to respond to each subscale, these examples may lead individuals to report a greater impairment, if their muscles are feeling sore. This is further supported when considering the response of MS, the subscale where the greatest change was observed at 24-48 h post exercise. This subscale specifically gives the example of "muscle soreness" and would likely reflect the response provided when an individual rates their muscle soreness.

5.4.5. Limitations & Further Research

It has been suggested within the literature that females may respond differently to muscle damaging exercise when compared to males. The difference in the muscle damage response between sexes is suggested to be due to circulating oestrogen levels (124). To control for this, analyses was conducted to confirm the responses of females were not different to males, following the EC. However, it is acknowledged that there was no control for menstrual cycle or contraceptive use in female participants, which has been associated with the response of certain indicators of muscle damage (126, 204, 205). Additionally, there was an imbalance the sample size between the male and female participants which were compared (9 male vs 6 female).

The current investigation was conducted using recreationally active participants, as they represent the type of individual who regularly conducts this type of exercise activity. As discussed previously (section 1.6.1), completing a bout of exercise is known to provide a protective effect against similar subsequent bouts of exercise, termed the RBE (3). These individuals who are regularly taking part in exercise may already have this protective effect, reducing the muscle damage response they receive following an EC. Research should control for the type of exercise activity which an individual regularly completes. This would provide insight into how individuals may be more susceptible to muscle damage following an EC if they are not accustomed to the exercise movements involved in the activity.

As discussed (section 1.6.2), there has been limited research investigating how training status may influence the muscle damage response and this has been conducted with individuals who do not reflect the regular inactive individual, who does not regularly take part in structured exercise (64, 96). However, in one investigation, “untrained” individuals were said to have a greater muscle damage response compared to cyclists and runners (64). Understanding how “inactive” individuals respond following EC activities could have implications for motivation and prolonged adherence to exercise. These individuals who are less accustomed to exercise activities may receive a more severe response following an EC and recover over a different time-course compared to regular exercisers. Research is needed to directly compare the response between regular exercisers and inactive individuals after completing conventional exercise activities (e.g., EC).

5.4.6. Conclusions

Completing an EC, representative of a regular day-to-day exercise activity, did not appear to result in muscle damage. Balance ability was not impaired following the EC, however, RS was reduced and remained impaired up till 96 h post exercise. The large amount of explosive plyometric jumping activities completed during the workout may explain why RS is impaired while balance ability is maintained in the days post exercise. Individuals reported reduced readiness to exercise 24-48 h post exercise, when considering constructs which represent physical and overall components of recovery. Functional and readiness to exercise outcomes appear more closely related to the response of muscle soreness compared to the other conventional indicators of muscle damage (force loss, CK), following the EC. Therefore, muscle damage response appears less severe after an EC compared to a conventional laboratory-based muscle damaging mode of exercise. This may have implications for the appropriate selection of recovery strategies and prescription of subsequent exercise following regular day-to-day exercise activities, which are informed by the muscle damage literature. Further research is required to investigate how inactive individuals may respond following common exercise activities compared to their more active counterparts. This could have implications for motivation and adherence to exercise, in a population who do not currently engage well with physical activity.

6. Comparing Recovery Between Downhill Running and an Exercise Class*

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*The work presented in this section has been completed by combing the data sets collected in the previous two investigations (section 4 & 5). This allows for additional analysis to be conducted which directly compares the responses observed following the DR and EC activities.

6.1 Introduction

In the previous two sections the muscle damage response has been investigated following two distinct types of exercise, DR (section 4) and a bodyweight EC (section 5). As discussed earlier (section 1.4), DR represents a common laboratory-based mode of exercise which exaggerates eccentric muscle actions and is commonly used to investigate responses to muscle damage. As expected, when recreationally active individuals completed DR (section 4.3) muscle damage was evident through changes observed in force generating ability, muscle soreness and myofibrillar proteins. Additionally, DR resulted in impairments in functional ability (RS & balance) and reduced self-reported readiness to exercise.

As discussed (section 5.1), EC activities represent a mode of exercise which is regularly conducted by active individuals in their day-to-day lives (198). ECs are often comprised of large full body movements, containing both eccentric and concentric phases of muscle action, using the resistance of bodyweight. As highlighted (section 5.1), less is known about the muscle damage response following common exercise activities. When a bodyweight EC was completed in the previous investigation (section5.3), muscle damage did not appear evident, when considering the response of common indirect indicators of damage (force loss, muscle soreness, CK). Conflicting results were observed for the effect of the EC activity on functional ability. RS appeared impaired for a prolonged period post exercise, whereas no impairment was observed in balance ability. Self-reported readiness to exercise was reduced in the days following completing the EC.

It appears from the responses observed in the previous two chapters (section 4 & 5), that a different pattern of recovery may be occurring post completing DR compared to an EC. The magnitude and time-course of the recovery of common indirect markers appear to suggest DR results in more muscle damage than an EC. Additionally, DR appears to result in impaired balance ability post exercise which is not apparent following the EC. Both modes of exercise resulted in impairments in RS, with this appearing more prolonged after the EC activity. Both activities resulted in individuals reporting reduced readiness to exercise in the days immediately post exercise. The response and pattern of recovery appears most different between the DR and EC, 24-48 h post exercise. Directly comparing the responses following the DR and EC, would provide greater insight into how the time-course and magnitude of recovery may be different between the modes of exercise. This may have implications for the appropriate selection of recovery strategies and the correct prescription of subsequent exercise, in the days immediately following these types of activities. This understanding is vital to ensure individuals are able to reduce the risk of injury and may facilitate increased motivation and adherence to further exercise.

There has been limited research within the literature which has directly compared muscle damage following different types of exercise. Muscle damage and functional outcomes have been compared following dance and repeated sprinting modes of exercise (15). Additionally, the muscle damage response has been compared following different high intensity running protocols (101). However, the research so far has been primarily concerned with the responses observed following exercise replicating the demands of performance sport environments. Understanding how recovery from regular day-to-day exercise activities (EC) may differ to conventional muscle damaging modes of exercise (DR), is vital for understanding the recovery needs of individuals. As discussed (section 5.4), within the literature recovery interventions are frequently investigated following laboratory-based modes of exercise known to result in muscle damage (29-33). If the recovery response following an EC is different to conventional muscle damaging exercise, this will influence the prescription of appropriate recovery strategies, which may reduce the risk of injury and assist in increasing adherence to exercise.

6.1.1. Aims & Research Questions

The aim of this chapter is to directly compare recovery following DR and a simulated EC. The modes of exercise will be compared by conducting further analysis on the data sets collected and presented in the previous two thesis chapters (section 4 & 5). This will allow the responses of indirect markers of muscle damage, functional outcomes and self-reported readiness to exercise to be directly compared between the two conditions, over the 96-h recovery period. Additionally, planned comparisons will be conducted to compare differences between the conditions at 24 & 48 h post exercise. These comparisons are due to recovery appearing different between the two modes of exercise when considering the results presented in sections 4.3 & 5.3. The combined analysis will allow the following research questions to be addressed:

1) Is the muscle damage response different following DR and EC modes of exercise?
    a. Is muscle damage greater 24-48 h post DR compared to an EC?
2) Are functional outcomes affected differently following DR and EC activities?
    a. Are functional outcomes more impaired 24-48 h post DR compared to an EC?
3) Is self-reported readiness to exercise different following DR and EC activities?

a. Is self-reported readiness to exercise impaired more 24-48 h post DR compared to an EC?

6.2 Materials & Methods

6.2.1. Participants

Participants were those previously described in section 4.2.1 & 5.2.1. When combined this resulted in a total sample of 27 healthy, recreationally active adult volunteers, who reported participating in structured exercise two-five times per week (Table 1). Participants were assigned to either the DR or EC conditions based on their participation in the research presented in the previous two section 4 & 5. Prior to participating in the research participants were screened for contraindicators to exercise using the PAR-Q (Appendix H). As described previously (section 2.1) ethical approval to perform the research was granted by the University of Essex ethics committee and written informed consent was provided by all participants, prior to commencing experimental work.

Table 6-1. Participant demographics (mean ± SD) by condition.

Condition	n	Age (years)	Stature (m)	Mass (kg)	Body Mass Index ($Kg.m^2$)
DR	12	26.6 ± 7.4	1.78 ± 0.1	85.7 ± 11.0	26.9 ± 4.3
EC	15	33.6 ± 10.4	1.72 ± 0.1	72.6 ± 12.4	24.5 ± 3.5

Note: DR = Downhill running, EC = Exercise class; DR n=12 male, EC n=9 male

6.2.2. Procedures

In the week prior to completing the DR (Figure 4-1) or EC (Figure 5-1) participants attended the laboratory to complete familiarisation with all outcome measures. The following week participants attended the laboratory (Visit 1) to complete pre-exercise assessments in the following order: 1) SRSS 2) CK 3) MVIC & Muscle Soreness 4) RS 5) Y-balance test. Participants completed an initial warm-up at each visit following the assessment of CK, comprising of a 5-min run at 8 km.h^{-1} in the DR condition or ten bodyweight squats and lunges at low intensity in the EC condition. Participants were then required to complete either a DR (described section 4.2.2.i) or EC (described in section 5.2.2.i) exercise protocol; immediately post exercise participants completed a further MVIC assessment. Participants attended the laboratory at 24 h (Visit 2), 48 h (Visit 3), 72 h (Visit 4) and 96 h (Visit 5) post Visit 1, for repeat testing of all outcomes conducted in the same order as at pre-exercise. T The laboratory was kept at a consistent temperature (20 °C) and participants attended at the same time of day (± 1 h) across all visits, to minimise the influence of circadian rhythm on performance (184, 185). Participants were requested to refrain from completing structured exercise activities while participating in the research.

6.2.3. Measures

i. Isometric Force

Isometric force was assessed as previously described in section 2.2.1.

ii. Muscle Soreness

Muscle soreness was assessed using a VAS as previously described in section 2.2.2. Muscle soreness ratings were assessed by participants rating the pain or discomfort they perceived when completing the MVIC.

iii. Creatine Kinase

Creatine Kinase assays were conducted from venous blood samples as previously described in section 2.2.3.

iv. Balance

Balance was assessed using the Y-Balance test as previously described in section 2.2.4.

v. Reactive Strength

RS was determined using the RSR from DJs as previously described in section 2.2.5.

vi. Readiness to Exercise

Self-reported readiness to exercise was measured using the SRSS as previously described in section 2.2.6.

6.2.4. Statistical Analysis

Two-way ANOVA (2 x 5) were used to determine any effect of time, condition or time x condition interaction for indirect markers of muscle damage and functional outcomes, as previously described in section 0; a two-way ANOVA (2 x 2) was used to determine any differences in isometric force immediately post exercise. To account for pre-exercise differences, percentage change from pre-exercise values were calculated and used in analysis for force loss, balance and reactive strength. Two-way ANCOVA were used to control for differences in readiness to exercise pre-exercise between conditions. Effect sizes from ANOVA & ANCOVA were reported as partial Eta squared (ηp^2) (191). Mean ± 95% confidence interval statistics were calculated and presented in figures; EMM were presented for readiness to exercise (Microsoft Excel, Microsoft Office 365 Pro Plus). Planned comparisons were conducted using independent samples t-tests to investigate differences between conditions 24 & 48 h post exercise, using change from pre-exercise values. Planned comparisons for readiness to exercise were conducted using the post-hoc analysis of pairwise comparisons for EMM; comparisons were only conducted on the subscales of PPC, MS, OS and OR. The comparisons were completed due to the observed recovery trends 24 & 48 h post exercise, following the DR and EC activities in the previous experimental chapters (section 4 & 5). Effect sizes (*g)* were calculated for differences between condition in change from pre-exercise scores 24 & 48 h post exercise (192, 193).

6.3 Results

6.3.1. Indirect Markers of Muscle Damage

i. Isometric Force

Isometric force (Figure 6-2) was reduced ($F = 40.82$, $p = 0.001$, $\eta p^2 = 0.62$) immediately post exercise with no difference in the reduction between conditions ($F = 1.67$, $p = 0.208$, $\eta p^2 = 0.06$). There was an effect for time on isometric force ($F = 3.65$, $p = 0.023$, $\eta p^2 = 0.13$), with force reduced ($p = 0.004$) at 24 h compared to pre-exercise; there was no effect for condition ($F = 3.22$, $p = 0.085$, $\eta p^2 = 0.11$) or time x condition ($F = 1.66$, $p = 0.191$, $\eta p^2 = 0.06$) interaction. Force was reduced to a greater extent at 24 h ($t = -2.12$, $p = 0.023$, $g = 0.80$) but not at 48 h ($t = 1.57$, $p=0.063$, $g = 0.59$) in the DR condition compared to the EC condition.

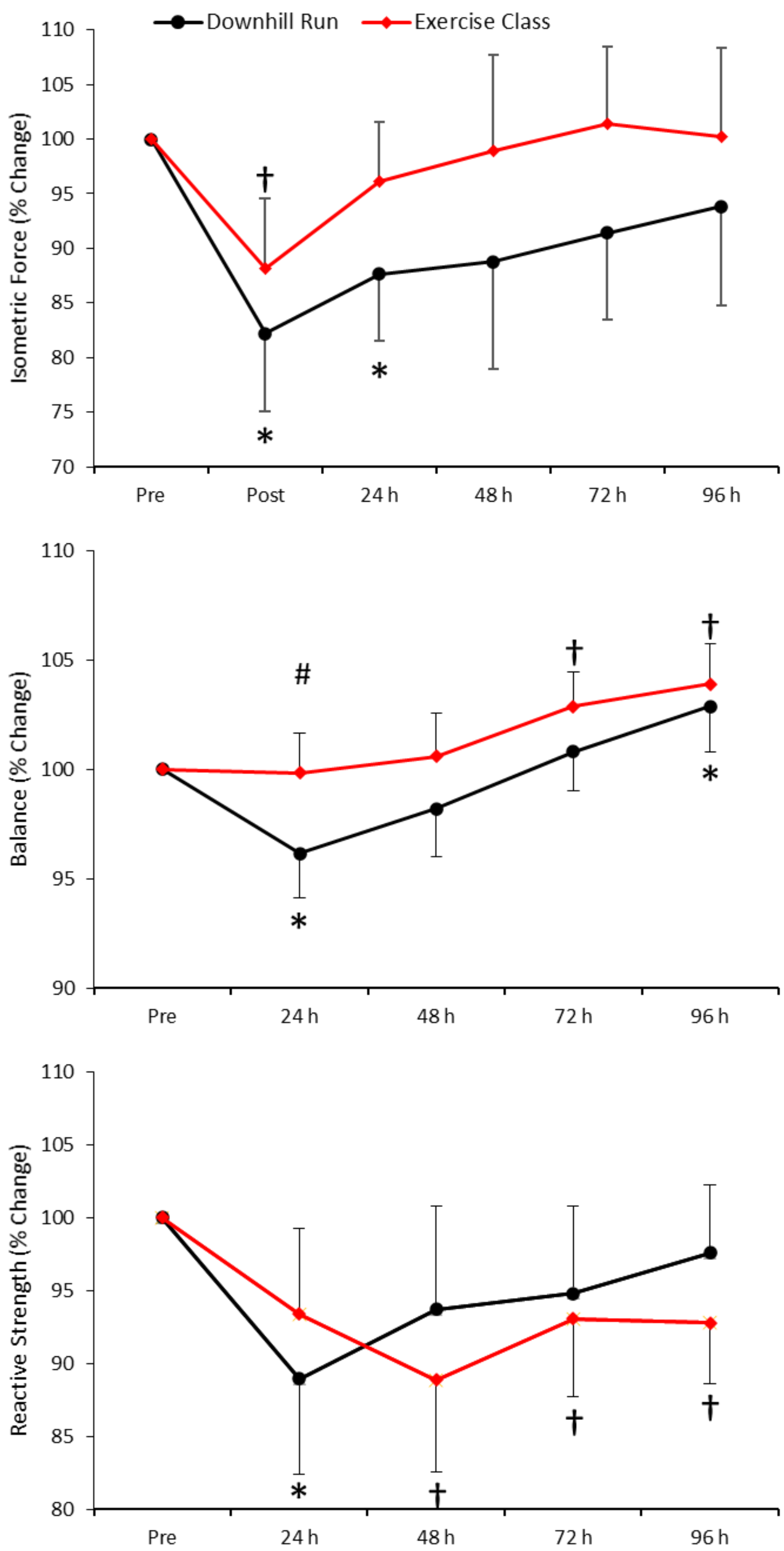
ii. Muscle Soreness

There was an effect for time ($F = 23.93$, $p = 0.001$, $\eta p^2 = 0.49$) and a time x condition interaction ($F = 4.74$, $p = 0.02$, $\eta p^2 = 0.16$) for muscle soreness, with muscle soreness reduced at 24 h ($p = 0.001$) and 48 h ($p = 0.008$) compared to pre-exercise (Figure 6-2). There was no effect of condition for muscle soreness condition ($F = 7.86$, $p = 0.100$, $\eta p^2 = 0.24$) Muscle soreness increased to a greater extent at 24 h ($t = 2.34$, $p = 0.017$, $g = 0.92$) and 48 h ($t = -1.96$, $p = 0.034$), $g = 0.76$) in the DR condition compared to the EC condition.

iii. Creatine Kinase

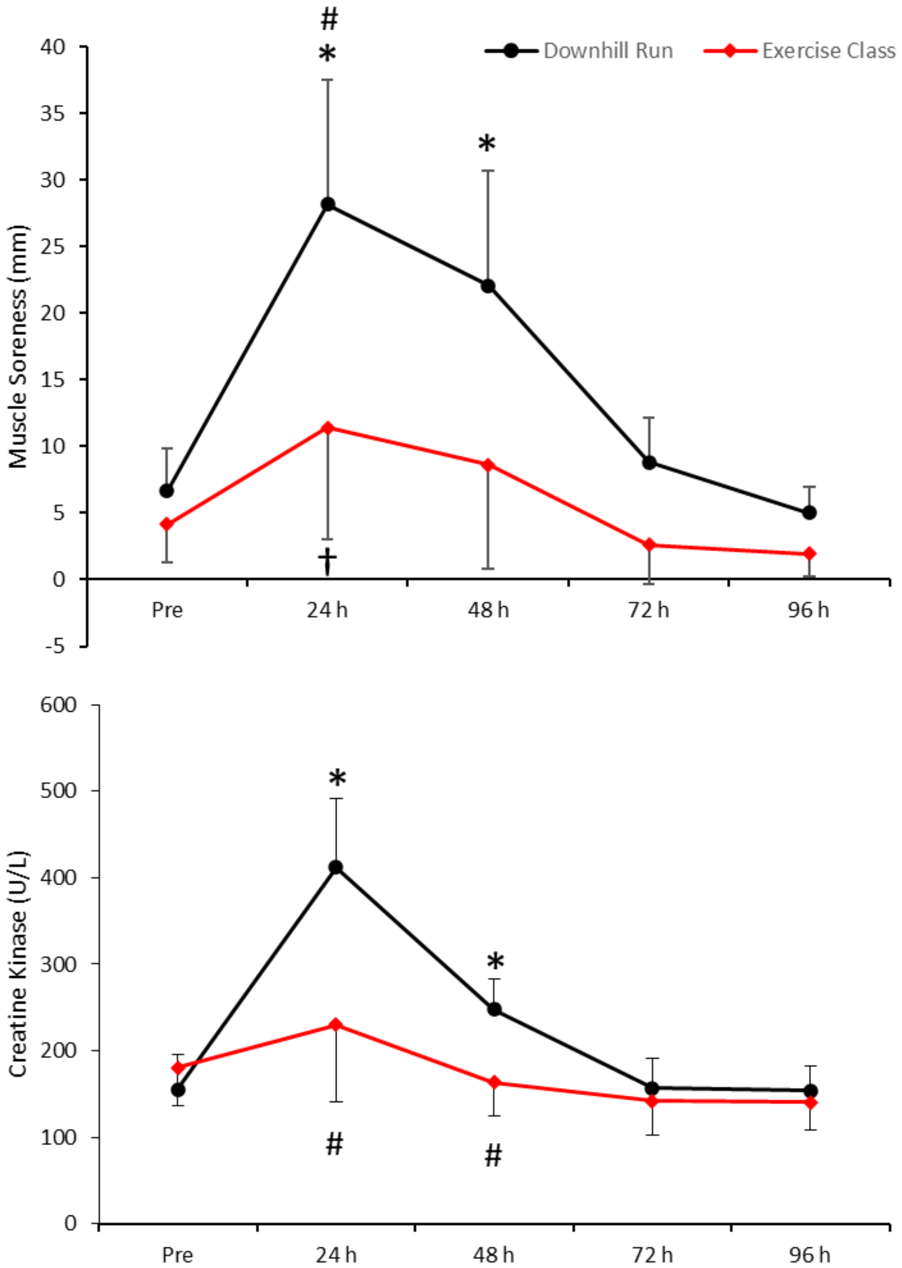
There was an effect for time ($F = 32.85$, $p = 0.001$, $\eta p^2 = 0.67$), condition ($F = 4.77$, $p = 0.044$, $\eta p^2 = 0.23$) and time x condition interaction ($F = 10.41$, $p = 0.001$, ηp^2

= 0.39) for CK, with CK reduced ($p = 0.001$) at 24 h compared to pre-exercise (Figure 6-2). CK increased to a greater extent at 24 h ($t = -3.87$, $p = 0.001$, $g = 1.83$) and 48 h ($t = -4.16$, $p = 0.001$, $g = 1.93$) in the DR condition compared to the EC condition.



Note: * denotes significant change (p < 0.05) from pre-exercise in downhill running condition; † denotes significant change (p < 0.05) from pre-exercise in exercise class condition; # denotes significant (p < 0.05) difference between conditions

Figure 6-1. **Recovery of isometric force, balance and reactive strength (mean ± 95% CI's) up to 96 h post a downhill run (n = 12) or simulated exercise class (n = 15)**.



Note: * denotes significant change (p < 0.05) from pre-exercise in downhill running condition; † denotes significant change (p < 0.05) from pre-exercise in exercise class condition; # denotes significant (p < 0.05) difference between condition

Figure 6-2. **Recovery of muscle soreness and Creatine Kinase (mean ± 95% CI's) up to 96 h post a downhill run (n = 12) or exercise class (n = 15).**

6.3.2. Functional Assessments

i. Balance

There was an effect for time ($F = 22.75$, $p = 0.001$, $\eta p^2 = 0.48$) and condition ($F = 4.37$, $p = 0.047$, $\eta p^2 = 0.15$) but no time x condition interaction ($F = 2.48$, $p = 0.069$, $\eta p^2 = 0.09$) for balance, with balance reduced at 24 h ($p = 0.050$) and increased at 72 ($p = 0.040$) & 96 h ($p = 0.001$) compared to pre-exercise (Figure 6-1). Balance was reduced to a greater extent at 24 h ($t = 2.83$, $p = 0.005$, $g = 1.05$) and 48 h ($t = 1.68$, $p = 0.050$, $g = 0.63$) in the DR condition.

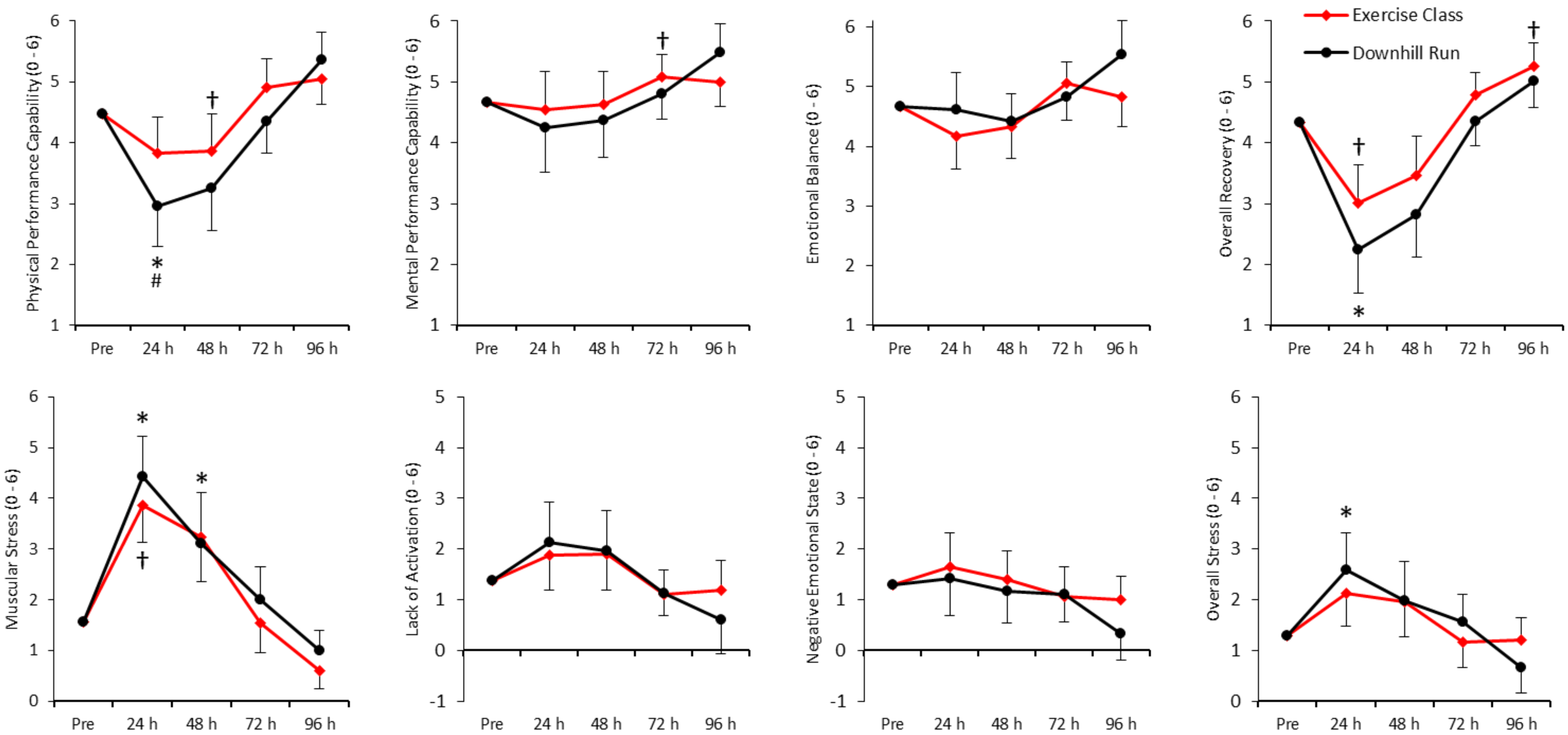
ii. Reactive Strength

There was an effect for time on RS ($F = 6.25$, $p = 0.001$, $\eta p^2 = 0.20$), with RS reduced at 24 ($p = 0.004$), 48 ($p = 0.009$), 72 ($p = 0.049$) and 96h ($p = 0.043$) compared to pre-exercise (Figure 6-1); there was no effect of condition ($F = 0.30$, $p = 0.586$, $\eta p^2 = 0.01$) or time x condition interaction ($F = 1.78$, $p = 0.166$, $\eta p^2 = 0.07$). The reduction in RS observed at 24 ($t = 0.36$, $p = 0.182$, $g = 0.36$) & 48 h ($t = -1.08$, $p = 0.145$, $g = 0.41$) was similar between conditions.

6.3.3. Readiness to Exercise

There was an effect for time on PPC ($F = 11.63$, $p = 0.001$, $\eta p^2 = 0.33$), OR ($F = 16.71$, $p = 0.001$, $\eta p^2 = 0.41$) and MS ($F = 22.37$, $p = 0.001$, $\eta p^2 = 0.48$); no effect of time was evident on MPC ($F = 2.34$, $p = 0.068$, $\eta p^2 = 0.10$), EB ($F = 1.08$, $p = 0.363$, $\eta p^2 = 0.04$), LOA ($F = 2.80$, $p = 0.062$, $\eta p^2 = 0.11$), NES ($F = 2.22$, $p = 0.094$, $\eta p^2 =$

0.09) and OS ($F = 1.56$, $p = 0.206$, $\eta p^2 = 0.06$) (Figure 6-3). There was no effect of condition on PPC ($F = 2.61$, $p = 0.119$, $\eta p^2 = 0.10$), MPC ($F = 0.10$, $p = 0.760$, $\eta p^2 = 0.01$), EB ($F = 0.93$, $p = 0.344$, $\eta p^2 = 0.04$), OR ($F = 3.56$, $p = 0.071$, $\eta p^2 = 0.13$), MS ($F = 0.91$, $p = 0.351$, $\eta p^2 = 0.04$), LOA ($F = 0.04$, $p = 0.841$, $\eta p^2 = 0.01$), NES ($F = 0.81$, $p = 0.377$, $\eta p^2 = 0.03$) & OS ($F = 0.08$, $p = 0.786$, $\eta p^2 = 0.01$). There was a time x condition interaction for PPC ($F = 2.72$, $p = 0.050$, $\eta p^2 = 0.10$); no interaction was evident for the MPC ($F = 1.59$, $p = 0.211$, $\eta p^2 = 0.06$), EB ($F = 1.76$, $p = 0.162$, $\eta p^2 = 0.07$), OR ($F = 0.57$, $p = 0.599$, $\eta p^2 = 0.02$), MS ($F = 0.64$, $p = 0.559$, $\eta p^2 = 0.026$), LOA ($F = 0.93$, $p = 0.412$, $\eta p^2 = 0.04$), NES ($F = 0.87$, $p = 0.460$, $\eta p^2 = 0.04$) or OS ($F = 1.94$, $p = 0.131$, $\eta p^2 = 0.08$). PPC was reduced to a greater extent ($p = 0.026$) at 24 h in the DR condition; OR ($p = 0.060$), MS ($p = 0.148$) and OS ($p = 0.173$) were not impaired to a greater extent in the DR condition at 24 h. PPC ($p = 0.089$), OR ($p = 0.089$), MS ($p = 0.418$) and OS ($p = 0.477$) were not impaired to a greater extent at 48 h in the DR condition.



Note: * denotes significant change ($p < 0.05$) from pre-exercise in downhill running condition; † denotes significant change ($p < 0.05$) from pre-exercise in exercise class condition; # denotes significant ($p < 0.05$) difference between condition

Figure 6-3. **Recovery of readiness to exercise (EMM ± 95% CI's) up to 96 h post a downhill run (n = 12) or exercise class (n = 15).**

6.4 Discussion

The aim of this chapter was to directly compare recovery following DR and a simulated EC. This was conducted through further analysis on the data sets collected and presented in the previous two thesis chapters (section 4 & 5).

6.4.1. Muscle Damage

The first aim of this investigation was to determine if the muscle damage response was different following completing DR compared to a bodyweight EC. Over the 96 h recovery period, there was no significant difference in the pattern of force reduction between the two conditions. However, there was a clear difference in the pattern of force loss and recovery 24-48 h post exercise. In contrast to isometric force, there were significant differences between condition in the pattern of recovery observed for muscle soreness and CK over the 96 h period. Following the DR, the increase observed from pre-exercise in muscle soreness and CK was consistently greater than in the EC condition; at 24-48 h the magnitude of difference was very large. When the responses across all three indirect indicators of muscle damage are considered together, this suggests completing DR results in a greater amount of muscle damage 24-48 h post exercise compared to an EC. This is interesting, if an EC results in less muscle damage, less recovery time may be required before completing subsequent exercise compared to following conventional muscle damaging exercise protocols (i.e., DR).

6.4.2. Functional Capability

The second aim of this investigation was to determine if the recovery of functional outcomes was different following DR and EC activities. There was no significant difference in the pattern of balance recovery over the complete 96 h period between conditions. However, similar to what was observed for indicators of muscle damage, balance ability was more greatly impaired following the DR compared to the EC, 24-48 h post exercise. The decline in balance 24 h post exercise was 3.2% greater in the DR condition compared to the EC condition. This may have implications for providing advice on appropriate recovery following these types of activities. As discussed (section 4.4), a decline in balance ability of 4% has been associated with an increased risk for injury (142). Therefore, individuals who exercise 24 h post completing DR may be more likely to get injured than those who exercise the day following an EC. As observed previously (section 4.3.2 & 5.3.4), repeatedly completing the balance assessment each day appears to result in a learning effect and subsequent increase balance ability. This learning effect occurred more rapidly following the EC, with balance increased 72 h post exercise compared to the DR condition where this became evident at 96 h. It is interesting that this learning effect is evident more quickly (72 vs 96 h) following the EC. The greater reduction in balance ability post DR may have masked this learning effect, as impaired balance would have prolonged the number of days required before this effect was observed. Therefore, the learning effect on this balance test may occur more rapidly following modes of exercise which do not impair balance. As discussed (section 5.4.2), further research is required to investigate factors which may influence performance on the balance test when used to test individuals daily. This insight is vital to ensure the balance test is able to be used appropriately to monitor acute recovery from exercise.

In contrast to balance, the pattern observed in the response of RS over the 96 h recovery period was similar between conditions. Both conditions resulted in a significant decline in RS 24-48 h post exercise and the magnitude of this decline was similar for both types of exercise. Interestingly, there was a trend towards a more prolonged decline in the EC condition, with a moderate to large difference between conditions at 96 h. As discussed previously (section 5.4.2) the prolonged impairment observed in RS following the EC may be due to the large amount of explosive plyometric jumping actions conducted during the exercise. Therefore, following both modes of exercise recovery would be required before completing exercise which involves explosive exercise movements. The responses of balance and RS indicate there may be a need for specific measures, tailored and sensitive to the mode of exercise, to ensure recovery is monitored accurately. Further research is required investigating the RS response with additional conventional day-to-day modes of exercise (i.e., gym based exercise, spin classes etc.). Those employing exercise which is less explosive may impair RS to a lesser extent and result in a RS response that would be significantly different to conventional muscle damaging exercise. The responses of balance and RS indicate there may be a need to ensure measures are sufficiently sensitive and bespoke, to detect impairments and monitor recovery based on the mode of exercise.

6.4.3. Readiness to Exercise

The final aim of this investigation was to determine if there was a difference in an individual's readiness to exercise following DR compared to an EC. The readiness to exercise response over the complete 96 h was not significantly different between conditions, across all subscales of readiness to exercise. Interestingly, a similar pattern is observed following both modes of exercise, across the physical and overall subscales (PPC, OR, MS and OS). Recovery is reduced and stress increased 24-48 h post exercise, before returning to or superseding pre-exercise levels. Across the mental and emotional subscales (EB, LOA, NES and OS) no clear trend is evident, suggesting completing either mode of exercise does not affect these components of readiness to exercise. As highlighted previously (section 4.4.3 & 5.4.3), when considering the response of readiness to exercise following both the DR and an EC, it is the physical and overall constructs of readiness to exercise in which impairments are observed. Therefore, these subscales may be most important when using readiness to exercise to monitor acute recovery.

Although readiness to exercise did not appear different between the modes of exercise over the complete 96 h period, there was a pattern towards greater impairment in the DR condition 24-48 h post exercise. The DR resulted in a significantly greater impairment in PPC 24 h post exercise compared to the EC. At 24 h, although not statistically significant, it is apparent the values for MS, OR and OS following the DR are all greater, than when compared to the EC. Additionally, though not statistically significant, the values for PPC, OR and OS at 48 h are great following the DR than when compared to the EC. When you consider these responses together over the 24-48 h period, it may suggest a pattern towards readiness being more impaired following the DR compared to the EC. As described previously, this is evident across four subscales (PPC, MS, OR, OS) which appear to respond following both exercise conditions and may provide most value when assessing readiness to exercise (section 4.4.3 & 5.4.3). This is interesting and it may be expected that the difference between conditions would be greater as the DR resulted in significantly more muscle damage. If readiness is more reduced following the DR, this suggests motivation to complete further exercise could be reduced in the days post muscle damaging activities. For athletic populations this could lead to detriments in performance and for regular exercisers this could result in reduced adherence to subsequent exercise. Further research is required to support this assertation comparing the readiness to exercise response following conventional muscle damaging modes of exercise and “real world” exercise activities.

6.4.4. Monitoring Recovery

It is apparent across a range of assessments including indirect markers of muscle damage, functional outcomes and self-reported readiness to exercise, that there are differences in recovery between the conventional muscle damaging mode of exercise (DR) and the regular exercise activity (EC). Over the complete 96 h period recovery may not appear different between the two modes of exercise, however, 24-48 h post exercise, individuals were less recovered when they completed the DR. Interestingly, when considering only a single type of outcome (i.e., indirect markers or functional assessment), this does not provide a complete picture of the recovery state and needs of the individuals. Considering conventional muscle damage indicators alone, it is clear that DR causes more damage than an EC. However, RS and readiness to exercise were still impaired following the EC. Therefore, when only considering conventional indicators of muscle damage, it suggests individuals do not need to recover and are suitable to complete further exercise. When considering the complete set of assessments, it is clear this may not be the case. To facilitate optimum recovery and select appropriate exercise, the reduced RS and readiness to exercise would need to be addressed. Taking a more holistic approach to recovery monitoring and management, using a set of assessments, appears more appropriate than utilising a sole assessment. These assessments may also be more accessible in sport and exercise environments compared to some conventional laboratory-based measures of muscle damage and provide vital information which may reduce injury risk and increase motivation to complete further exercise.

6.4.5. Limitations & Further Research

As discussed, a learning effect appeared evident for the balance test following both modes of exercise (DR & EC). This learning effect may have influenced balance scores over the 96 h recovery period. However, the conditions in which the balance test was administered were identical across both the DR and EC investigations. Any improvement in balance may therefore be expected to be similar following both modes of exercise. Consequently, when combing the data and comparing between conditions, a difference would still be expected to be observed at a specific time point. I.e., if balance was increased due to learning at 24 h following DR, it would also be increased following the EC at 24 h. Based on this, differences between condition may still reflect the differences in recovery between conditions . When a modified version of the SEBT (similar to the Y-balance test) was used to monitor recovery from muscle damaging exercise, no learning effect was present, when assessed daily (16, 142). The modified version of the SEBT does not provide a visible reach distance to participants and is not conducted using the Y-balance test apparatus. As discussed previously, the visibility of reach distance may be influencing performance on the balance test, when used for repeated daily assessment. A recent meta-analysis supports the lower limb Y-balance test being a reliable and valid measure of dynamic neuromuscular control (18). This would suggest it is an appropriate measure to be included when assessing balance recovery following exercise. Therefore, the observed learning effect warrants further investigation. It is important to understand what may be contributing to this effect, to determine the suitability of the Y-balance test as a measure to monitor repeated acute recovery (i.e., day-to-day).

The data set collected and included as the EC condition, included both male and female participants. As discussed previously (section 5.4.5), it has been suggested within the literature that females may respond differently to muscle damaging exercise when compared to males and this can influence indicators of muscles damage (126, 204, 205). To control for this, analysis was conducted to confirm the responses of females were not different to males, following the EC (described in section 5.2.4). However, comparing the EC condition containing both male female participants, with the DR condition containing only male participants, presents a limitation to the current work.

The current research investigated the differences between two types of exercise using a between subject's design. Future work should complete investigations within participants, to alleviate any potential inter-individual differences in participant characteristics or responses to exercise. The individuals who participated were those considered recreationally active, who reported taking part in structured exercise 2-5 times per week. Further research should consider how training status may affect the muscle damage response. It would be particularly of interest to understand how less active or inactive individuals respond to these types of exercise compared to their more active counterparts. If less active individuals were to recover differently this could have implications for their recovery needs and adherence to subsequent exercise. Research should continue to investigate other modes of exercise which are regularly undertaken in day-to-day exercise settings and compare recovery with common muscle damaging exercise activities. This would provide more insight into potential muscle damage and recovery responses following common exercise activities, to facilitate enhanced recovery strategies.

6.4.6. Conclusion

In conclusion, it appears that the conventional laboratory mode of muscle damaging exercise (DR) results in a greater muscle damage response compared to the “real world” EC activity. The DR resulted in a reduction in balance which was not observed following the EC, however, both modes of exercise caused a prolonged reduction in RS. The increased damage and reduced balance may leave individuals more susceptible to injury if they were to conduct further exercise 24-48 h post the DR. Individuals who completed the EC may be suitable to exercise sooner, however, should avoid activities involving rapid stretch-shortening actions, as RS still appears reduced and could increase the risk of injury from these type of muscle actions. The difference in the readiness to exercise of individuals between the conditions was less pronounced compared to the observations in physiological and functional outcomes. Overall, the DR may have impaired readiness to a greater extent than the EC, with this most evident in constructs of recovery related to an individual’s physical capability, however, further investigation is warranted. These findings could have implications for selecting the appropriate recovery strategies, reducing injury risk and increasing adherence to subsequent exercise.

7. Muscle Soreness and Readiness to Exercise in Active and Inactive Adults Following a Virtual Exercise Class

7.1 Introduction

In the previous experimental chapters, the focus has been on the muscle damage response following conventional muscle damaging exercise (DR, section 4) and novel exercise which is representative of that frequently conducted in day-to-day life (EC, section 5). Additionally, the effect the modes of exercise have upon functional and readiness to exercise outcomes has been considered. These responses have been investigated in individuals who are considered recreationally active, regularly taking part in structured exercise 2-5 times per week. As discussed (section 5.4.5), understanding how the response compares in less active individuals, would provide further insight into the recovery needs of individuals who do not regularly engage with physical activity. Increasing population levels of physical activity is an issue of great interest in modern society (206). If less active individuals have a more severe response when beginning regular exercise activities, this may discourage them from participation in further physical activity. Therefore, this may present a barrier to exercise and affect adherence to exercise in this population.

As discussed previously (section 1.6.2), there has been very little research which has directly compared the muscle damage response between individuals depending on their training status. The investigations which have been conducted often involve comparing individuals from different training or sporting backgrounds (e.g., runners vs cyclists), to provide insight into how these activities might result in muscle damage (64). Research frequently employs untrained individuals alone to investigate the muscle damage response to exercise, as these individuals do not possess a protective effect from being accustomed to the type of exercise. However, there are only two studies which have directly compared inactive participants with their trained counterparts (64, 96).

In the first study, the muscle damage response was compared between long distance runners, cyclists and untrained individuals following an eccentric knee extensor exercise protocol (64). The untrained condition received more muscle damage, as evidence by reduced force / torque generating ability. No difference was observed in the muscle soreness response between conditions; the measurement was only conducted 48 h post exercise, which would not allow for any potential prior muscle soreness between conditions to be observed (e.g., 24 h). The untrained individuals were described as “physically active” and able to produce a similar amount of torque and work during the exercise protocol compared to the other conditions. In the second study, trained and untrained individuals were compared following a muscle damaging squat exercise protocol (96). The observed muscle damage response and recovery were similar between conditions. However, there was a moderate to large effect observed between conditions in measures of muscle soreness and peak power. The untrained condition were classified due to having no resistance training experience, while still being active in sport for at least two years and completing three or more exercise sessions per week. Therefore, the responses observed in these “untrained” individuals may not reflect the response that would be observed with individuals who do not conduct regular physical activity. As discussed, understanding the response in individuals who do not regularly engage in physical activity, compared to their more active counterparts, could provide crucial insight into possible barriers to exercise and methods to increase adherence to exercise.

In the previous investigation (section 5.3.2) muscle soreness was shown to be increased after completing a bodyweight EC. Additionally, physical and overall components of readiness to exercise were impaired over a similar time-course. Taken together this could have implications for the motivation and suitability of an individual to conduct further exercise in the days post completing EC. These observations were apparent in individuals who are considered recreationally active and take part in structured exercise regularly (2-5 times per week). Comparing the response to an EC between individuals who are considered physically active and inactive, may highlight differences in the recovery needs between these individuals. This could have implications for the selection of recovery strategies and adherence to subsequent exercise sessions. Furthermore, this may indicate the need to tailor EC sessions specifically for individuals who are not accustomed to regular physical activity.

7.1.1. Aims & Research Questions

The aim of this research is to compare recovery from a bodyweight EC, between individuals who are regularly physical active and individuals who are physically inactive. The investigation shall have the following research questions:

1) Is muscle soreness different between physically active and inactive individuals following an EC?
2) Is readiness to exercise different between physically active and inactive individuals following an EC?

7.2 Materials & Methods

7.2.1. Participants

Participants were 24 healthy adult volunteers, who reported taking part in structured physical activity up to five times per week (Table 7-1). Participants who reported taking part in structured exercise at least two times per week were assigned to the physically active (Active) condition; those who reported one session or less per week were assigned to the physically inactive (Inactive) condition. The active group reported completing regular exercise activities (resistance training, cycling, running, swimming); they had not completed exercise activities representative of that conducted during an EC in the previous three months. Prior to participating in the research individuals were screened for contraindicators to exercise using the PAR-Q (Appendix H). As described previously (section 2.1) ethical approval to perform the research was granted by the University of Essex ethics committee and written informed consent was obtained from all participants.

Table 7-1. Participant characteristics (mean ± SD) by condition.

Condition	n	Age (years)	Stature (m)	Mass (kg)	Body Mass Index ($Kg.m^2$)	Exercise Sessions per Week	Well-being
Active	13	30.2 ± 6.5	1.72 ± 0.11	77.0 ± 10.3	26.3 ± 3.9	3.5 ± 0.9	47.8 ± 8.4
Inactive	11	31.3 ± 4.2	1.72 ± 0.14	68.4 ± 16.2	22.7 ± 2.5	0.6 ± 0.5	48.0 ± 4.7

Note: Active n=6 male, Inactive n=5 male; Well-being assessed using the WEMEBS

7.2.2. Procedures

Prior to completing the exercise session, all participants were provided with video tutorials for the main exercise movements used in the workout, including options for scaling. Immediately before completing the exercise participants completed pre-exercise assessments in the following order: 1) SRSS 2) Muscle Soreness 3) Mental well-being assessment (Figure 7-1). Participants then completed a 40-min virtual EC including an initial warm-up phase; immediately post exercise participants reported session RPE and rating of fatigue (ROF). Participants completed further SRSS and muscle soreness assessments 24 & 48 h post exercise; measures were completed at the same time of day (± 1 h). Participants were requested to refrain from completing structured exercise activities while participating in the research.

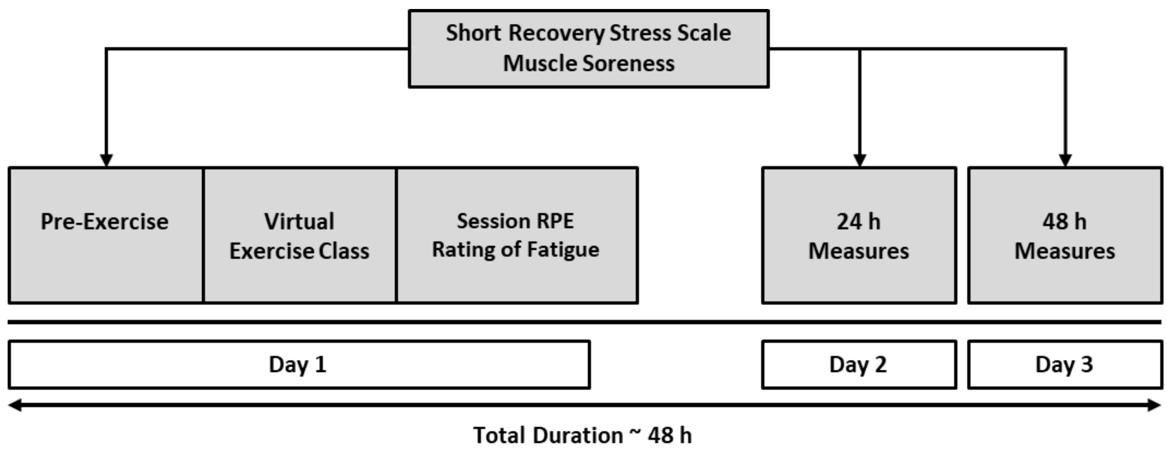


Figure 7-1. Schematic representation of the experimental protocol to conduct a virtual exercise class and monitor recovery up to 48 h post exercise.

i. Virtual Exercise Class

Participants completed a Les Mills^{TM} (Training: Cardio #01) virtually delivered bodyweight EC from their own home, led onscreen by a fitness instructor throughout (207). The workout was approximately 40-min in duration, including an initial structured warm-up and requiring the use of no equipment (Appendix L). Participants were advised to scale exercises or reduce the intensity or frequency of movements, to enable them to complete the maximum amount of exercise possible during the workout period. Due to the Covid-19 pandemic, it was not possible for investigators to be present and monitor the participants as they completed the virtual exercise class.

7.2.3. Measures

i. Muscle Soreness

Participants reported muscle soreness using a VAS as previously described section 2.2.2. Muscle soreness ratings were assessed by participants rating the pain or discomfort they perceived while holding a squatted position.

ii. Readiness to Exercise

Self-reported readiness to exercise was determined as previously described (section 2.2.6) using the SRSS.

iii. Well-being

Mental well-being was assessed using The Warwick-Edinburgh Mental Well-being Scale (WEMWBS) (208). Well-being was assessed as the research took place during the Covid-19 global pandemic, to determine any possible mental detriments compared to norms.

iv. Perceived Exertion and Fatigue

Perceived exertion was assessed immediately post exercise using the session RPE scale (209, 210). Fatigue was assessed immediately post exercise using the ROF scale (211).

7.2.4. Statistical Analysis

An a priori power analysis (G∗POWER 3.1 Software, Düsseldorf, Germany) was conducted to determine significant power at an α-level of 0.05. Muscle soreness data from the simulated EC investigation in the previous experimental chapter (section 5.3) were used to determine an effect size ($f = 0.65$), revealing a total required sample size of 24 participants. Two-way mixed ANOVA were used to determine any effect of time, condition or time x condition interaction for muscle soreness, as described previously in section 0. Two-way mixed ANCOVA were used to investigate any effect of time, condition or time x condition interaction for readiness to exercise after controlling for differences in pre-exercise scores. Post-hoc analysis of pairwise comparisons was conducted to compare between condition differences at 24 & 48 h. Independent samples t-test were used to investigate between condition differences in RPE and ROF post exercise. Mean ± 95% confidence intervals for muscle soreness and EMM ± 95% confidence intervals for readiness to exercise, were calculated and presented in figures (Microsoft Excel, Microsoft Office 365 Pro Plus). Mean ± standard deviation absolute values for readiness to exercise were presented in table. Effect sizes were calculated and reported using partial eta squared (ηp^2; ANOVA/ANCOVA) and hedges *g* (t-tests) (191-193). Descriptive statistics for RPE, ROF and muscle soreness, at all-time points are provided in Appendix M.

7.3 Results

7.3.1. Perceived Exertion & Fatigue

There was no difference in RPE (t = -1.29, p = 0.209, *g* = 0.52) or ROF (t = -1.73, p = 0.097, *g* = 0.70) between condition immediately post exercise (Figure 7-2).

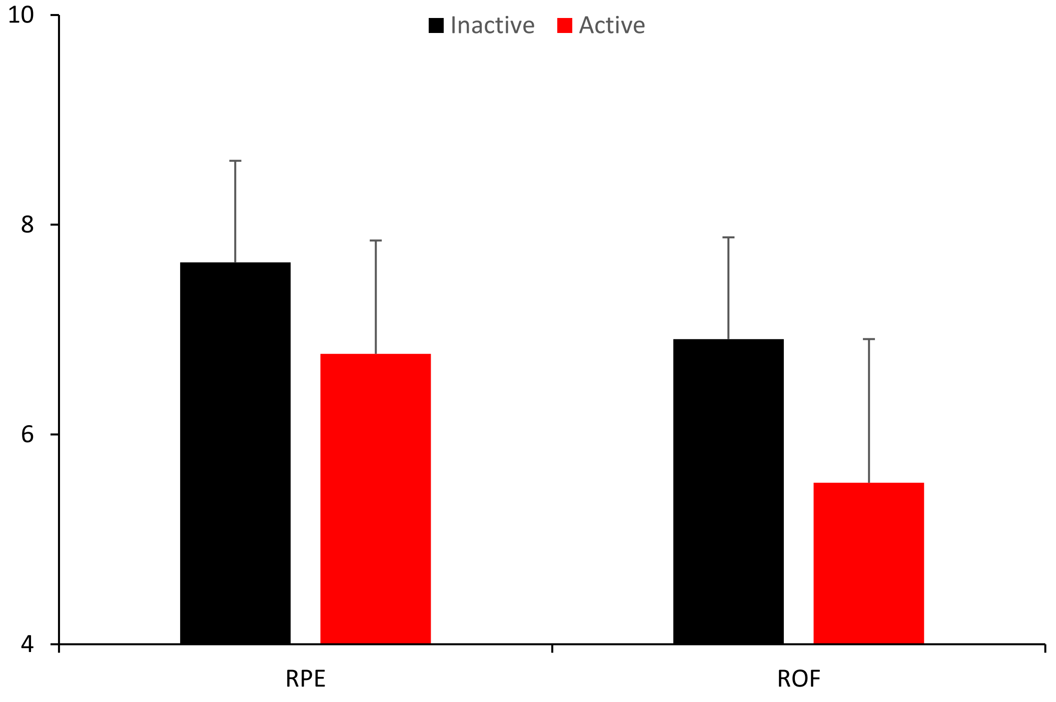
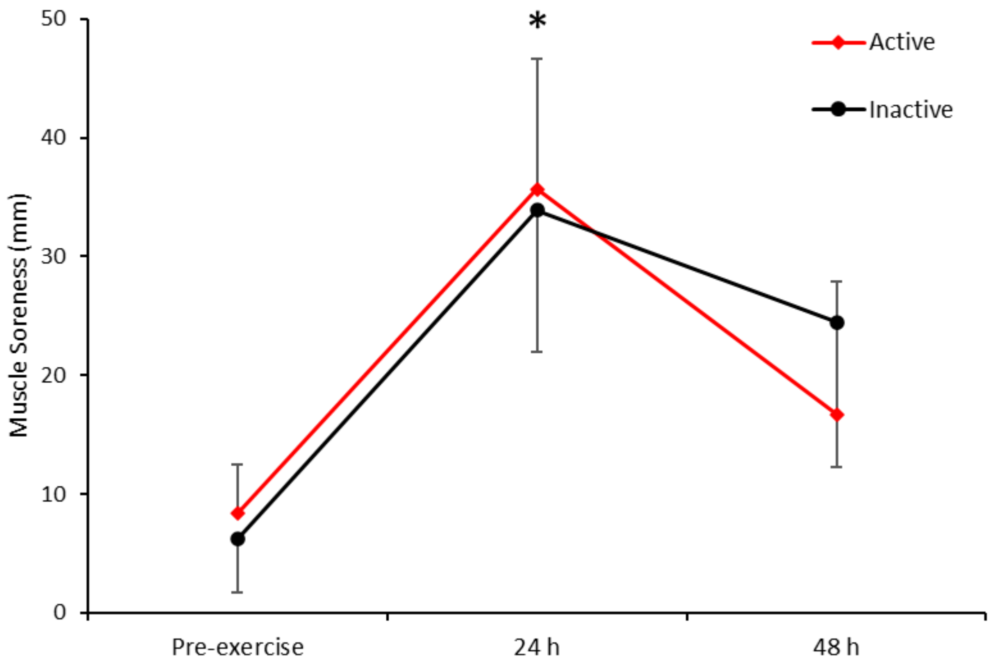


Figure 7-2. Session rating of perceived exertion (RPE; 6 - 20) and rating of fatigue (ROF; 0 - 10), for physically active (n = 13) and inactive (n = 11) individuals, measured immediately post completing a virtual exercise class (mean ± 95% CI's).

7.3.2. Muscle Soreness

There was an effect for time on muscle soreness ($F = 29.22$, $p = 0.001$, $\eta p^2 = 0.57$), with soreness increased ($p = 0.001$) at 24 h compared to pre-exercise (Figure 7-3); there was no effect for condition ($F = 0.06$, $p = 0.811$, $\eta p^2 = 0.01$) or time x condition interaction ($F = 1.23$, $p = 0.303$, $\eta p^2 = 0.05$).



Note: * denotes significant (p < 0.05) change from pre-exercise

Figure 7-3. Muscle soreness (mean ± 95% CI's) up to 48 h post completing a virtual exercise class in physically active (n = 13) and inactive (n = 11) individuals.

7.3.3. Readiness to Exercise

There was no main effect for time on any subscale of readiness to exercise when controlling for pre-exercise scores; PPC ($F = 0.00$, $p = 0.991$, $\eta p^2 = 0.00$), MPC ($F = 0.36$, $p = 0.553$, $\eta p^2 = 0.02$), EB ($F = 0.01$, $p = 0.947$, $\eta p^2 = 0.00$), OR ($F = 1.43$, $p = 0.245$, $\eta p^2 = 0.06$), MS ($F = 1.92$, $p = 0.180$, $\eta p^2 = 0.08$), LOA ($F = 0.76$, $p = 0.393$, $\eta p^2 = 0.04$), NES ($F = 0.13$, $p = 0.720$, $\eta p^2 = 0.01$) & OS ($F = 0.03$, $p = 0.872$, $\eta p^2 = 0.01$) (Figure 7-4). There was no main effect for condition on any subscale of readiness to exercise when controlling for pre-exercise scores; PPC ($F = 1.39$, $p = 0.253$, $\eta p^2 = 0.06$), MPC ($F = 1.86$, $p = 0.188$, $\eta p^2 = 0.08$), EB ($F = 0.58$, $p = 0.454$, $\eta p^2 = 0.03$), OR ($F = 0.06$, $p = 0.816$, $\eta p^2 = 0.01$), MS ($F = 1.38$, $p = 0.253$, $\eta p^2 = 0.06$), LOA ($F = 0.08$, $p = 0.787$, $\eta p^2 = 0.01$), NES ($F = 0.10$, $p = 0.750$, $\eta p^2 = 0.01$) & OS ($F = 0.17$, $p = 0.682$, $\eta p^2 = 0.01$). There was a time x condition interaction for overall stress ($F = 8.19$, $p = 0.009$, $\eta p^2 = 0.28$) when controlling for pre-exercise scores; no interaction was evident for PPC ($F = 0.01$, $p = 0.979$, $\eta p^2 = 0.00$), MPC ($F = 0.11$, $p = 0.744$, $\eta p^2 = 0.01$), EB ($F = 0.85$, $p = 0.367$, $\eta p^2 = 0.04$), OR ($F = 0.01$, $p = 0.943$, $\eta p^2 = 0.00$), MS ($F = 0.01$, $p = 0.956$, $\eta p^2 = 0.00$), LOA ($F = 3.15$, $p = 0.090$, $\eta p^2 = 0.13$) & NES ($F = 0.16$, $p = 0.694$, $\eta p^2 = 0.01$). Post-hoc analysis revealed OS was higher 24 h post exercise in the physically active condition ($p = 0.050$).

Table 7-2. Readiness to exercise (mean ± SD) absolute values up to 48 h post a virtual exercise class in physically active (n = 13) and inactive (n = 11) individuals.

Time	Group	Readiness to Exercise (0 – 6)							
		PPC	MPC	EB	OR	MS	LOA	NES	OS
Pre	Active	5.2 ± 1.1	5.5 ± 1.1	5.3 ± 1.2	5.2 ± 1.4	2.1 ± 0.9	3.1 ± 1.3	2.7 ±1.4	3.2 ± 1.5
	Inactive	3.8 ± 1.2	5.0 ± 0.9	5.2 ± 0.6	4.3 ± 1.5	2.7 ± 1.3	3.9 ± 1.6	3.1 ± 0.9	3.3 ± 1.4
24 h	Active	4.5 ± 0.8	5.6 ± 1.0	5.7 ± 1.2	4.2 ± 1.3	4.5 ± 1.1	3.4 ± 1.4	2.6 ± 1.2	3.6 ± 1.3*
	Inactive	4.2 ± 1.1	5.0 ± 1.1	5.2 ± 0.8	3.9 ± 1.1	4.8 ± 0.8	3.2 ± 1.4	2.5 ± 1.2	2.6 ± 1.2
48 h	Active	5.4 ± 0.8	5.8 ± 0.9	5.8 ± 1.2	5.2 ± 1.2	3.3 ± 1.5	2.5 ± 1.3	2.2 ± 1.1	2.2 ± 1.2
	Inactive	4.8 ± 1.1	5.3 ± 1.3	5.7 ± 1.3	5.0 ± 1.3	3.7 ± 1.3	3.5 ± 1.3	2.4 ± 1.0	2.9 ± 1.2

Note: Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS); * denotes significantly higher in active condition compared to inactive condition

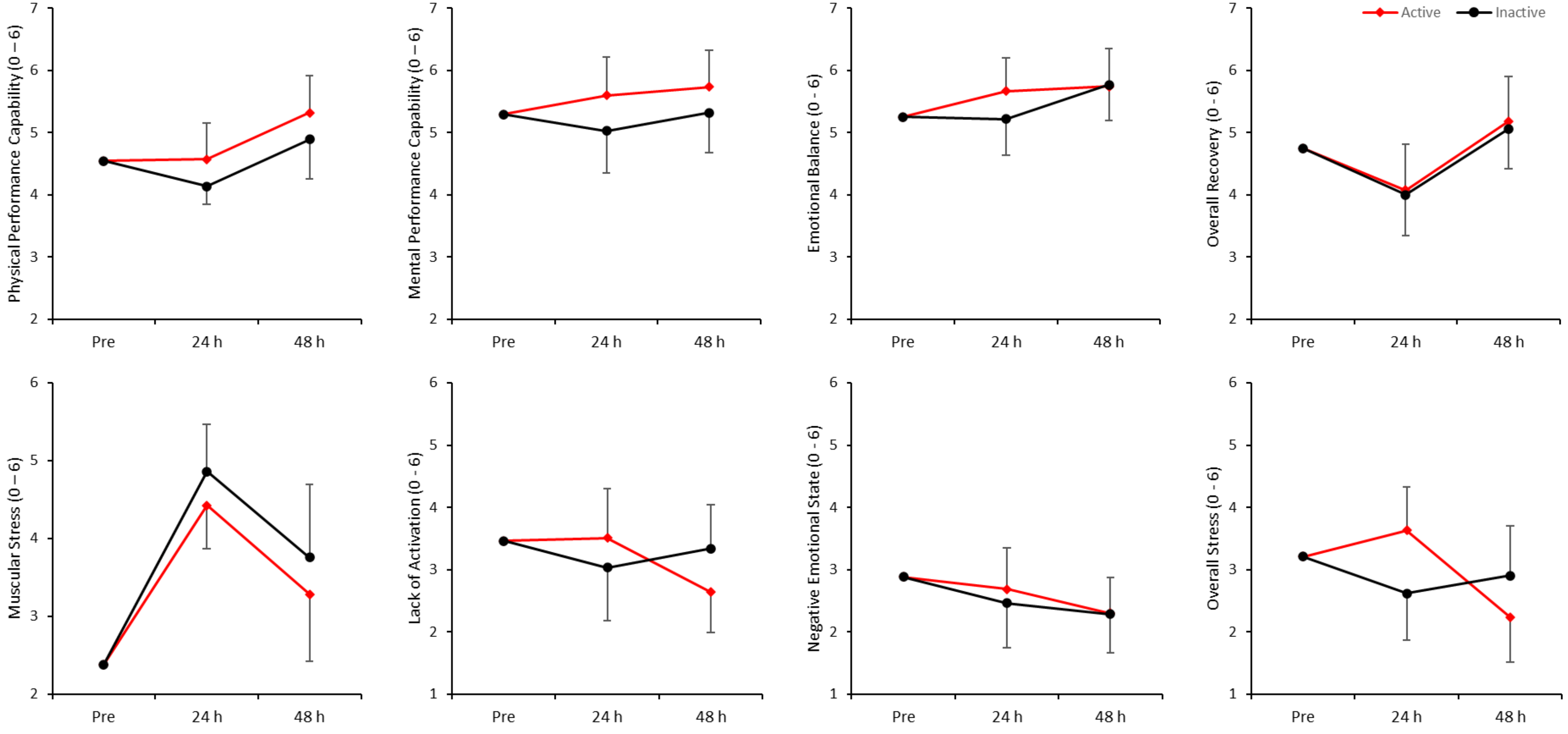


Figure 7-4. **Recovery of readiness to exercise (EMM ± 95% CI's) up to 48 h post a virtual exercise class in physically active (n = 13) and inactive (n = 11) individuals.**

7.4 Discussion

7.4.1. Muscle Soreness

The purpose of this investigation was to determine if the response to and recovery from a virtually delivered bodyweight EC, is different between physically active and inactive individuals. The muscle soreness response was similar between the active and inactive conditions, increasing 24 h post exercise before reducing at 48 h but remaining above pre-exercise levels. The time-course of the soreness response is similar to that observed when individuals completed a different EC in the previous investigation (section 5.3.2). It is interesting that the muscle soreness response was similar between the active and inactive individuals post exercise. This finding is similar to that observed previously, where runners, cyclists and untrained individuals reported a similar muscle soreness response post exercise (64). The inactive individuals who took part in this investigation were less physically active than those in previous research and did not regularly take part in exercise. Therefore, it was expected that the inactive individuals may receive a greater muscle soreness response post exercise.

The observed soreness response in this investigation is in contrast to the moderate to large effect observed in muscle soreness between trained and untrained individuals post squatting exercise (96). However, previously untrained individuals' indices of force loss were more impaired post exercise, compared to the more trained runners and cyclists, even though no difference in soreness was apparent (64, 96). Therefore, research should compare force loss between active and inactive individuals post completing an EC. This would provide greater insight into potential differences in the muscle damage response post EC, between active and inactive individuals.

7.4.2. Readiness to Exercise

The second aim of this research was to determine if readiness to exercise is different between active and inactive individuals, following an EC. Mental well-being was assessed and found to be just below the average for UK norms, while remaining above what would be considered impaired (212). Therefore, it is unlikely the ongoing global pandemic has influenced how individuals self-reported their readiness to exercise. There was no clear difference between conditions in readiness to exercise 24-48 h post exercise. This suggests following a bodyweight EC, both active and inactive individuals feel ready to conduct further exercise similarly.

A clear increase was observed for MS in both conditions at 24 h, before reducing towards pre-exercise levels at 48 h. The pattern of the muscular stress response was similar to the profile observed for muscle soreness. This may suggest when individuals self-report muscular stress they are reflecting the same sensation as when they report their muscle soreness. This is supported by the previous DR (section 4.3) and simulated EC (section 5.3) investigations, where similar response profiles were evident for muscle soreness and muscular stress. It is unexpected that the only component of readiness to exercise that would be affected is MS. Previously following the DR and EC activities, when muscular stress increased changes were observed in PPC, OR and OS. This may highlight how the MS component of readiness to exercise is more sensitive than the other reported physical and overall components. In section 4 (Table 4-2) & 5 (Table 5-2), the change in MS was associated with the greatest effect compared to other readiness sub-scales and would support this subscale being more sensitive to change. Understanding the sensitivity of change for the components of readiness to exercise is important in determining its suitability for monitoring recovery from exercise.

7.4.3. Active vs Inactive

When considered together, the observed responses in muscle soreness and readiness to exercise, suggest that physically active and inactive individuals recover similarly following a bodyweight EC. However, although not statistically significant, the inactive condition did report both greater exertion and fatigue, to a moderate-large effect, immediately post completing the workout. Therefore, inactive individuals may perceive the exercise to be more demanding and fatiguing, without recovery in subsequent days being adversely affected compared to physically active individuals.

7.4.4. Limitations & Further Research

In the current investigation it was not possible to control and monitor the quality, frequency and intensity of the exercise movements which both the physically active and inactive conditions completed during the workout. This may have influenced the observed responses an presents a limitation of the work. However, in completing the activity alone, participants conducted a virtual exercise class under conditions that reflect how they are regularly conducted across the world, when incorporated into regular exercise routines. Additionally, if participants had been observed it is possible this may have influenced their exercise behaviour while completing the EC. This highlights some of the challenges that are present, when looking to replicate the demands of regular exercise activities, as they are completed in day-to-day life. Further research is warranted to control for the volume of exercise completed during an EC workout. This would confirm if the similar responses post exercise between active and inactive individuals, are evident while completing the same amount of physical activity. If less active individuals recover similarly to their more active counterparts when completing the same exercise, they can be advised they will recover the same as those who frequently complete the activity, even though they may find the exercise more demanding initially. Conversely, if the similar response is due to less active individuals completing less activity during the workout, this has implications for prescribing lower intensity and less demanding workouts to allow individuals to become accustomed to new exercise activities.

7.4.5. Conclusion

In conclusion, following a bodyweight EC, physically active and inactive individuals recovered similarly when considering muscle soreness and readiness to exercise responses. However, individuals who are physically inactive may perceive they exert themselves more and feel more fatigued immediately post exercise, compared to those who are regularly active. Further research is required to confirm these assertions and determine how the quantity, quality and intensity of exercise completed during an EC, may contribute to the recovery response in active and inactive individuals. This could have positive implications for the encouragement strategies used to engage inactive individuals with exercise (i.e., you may feel sore but physically you are ready).

8. Conclusions and Implications of Research

8.1 Research Synopsis

The purpose of this thesis was to further investigate how the mode of exercise and environment in which it is conducted, influence the muscle damage response and recovery from exercise. The literature review identified four overarching research questions (section 1.7.2) which would be addressed to build upon the EIMD literature.

Question (1) was "Does conventional laboratory-based muscle damaging exercise affect functional outcomes?". This question built upon emerging research (see section 0) which evidenced impairments in functional outcomes post muscle damaging exercise (14-16, 27, 28, 62, 81-83, 87, 101-103, 105, 115, 116). Historically, EIMD has been investigated using laboratory based eccentrically biased exercise protocols, which are known to result in a large amount of muscle damage. Interestingly, research has not investigated the recovery of outcomes following conventional laboratory-based muscle damaging activities (e.g., eccentric contractions of elbow extensors / knee flexors, DR). Due to the large amount of damage induced using laboratory-based protocols they are frequently used to investigate the effectiveness of recovery strategies on EIMD (29-33). Understanding how functional outcomes may be affected in response to these laboratory-based modes of exercise may assist in the prescription and selection of recovery strategies following muscle damaging activities.

Question (2) was "Is self-reported psychological recovery affected by muscle damaging exercise?". Understanding how exercise which results in muscle damage may impact an individual's self-reported readiness to exercise, could have implications for motivation and adherence to further exercise. Currently research in this area is limited (see section 1.5.6), with only simple single scale assessments employed to assess readiness to exercise following muscle damaging activities (63, 71, 78). Investigating readiness to exercise following muscle damaging activities using a more complex assessment, may provide greater insight into the response and how it may affect an individual's adherence and motivation for subsequent exercise.

Question (3) was "Do common day-to-day exercise activities result in muscle damage?". Research has investigated EIMD extensively (discussed in section 1.4) using exercise protocols which are eccentrically biased and known to result in muscle damage. In recent years, there has been a shift towards evaluating muscle damage following sport specific modes of exercise (15, 16, 27, 28, 97-109). However, this has been primarily concerned with how muscle damage may occur in sport settings and how this may influence athletic recovery. Understanding the muscle damage response following exercise activities commonly conducted in day-to-day life would provide valuable insight into the recovery needs of recreationally active individuals. This could aid in the selection and implementation of recovery strategies and facilitate adherence to further exercise sessions, while reducing the risk of injury. Additionally, a sub-question (i) was included to determine "How does the response compare between more and less active individuals??". Understanding how individuals who do not regularly engage in physical activity may respond differently compared to their more active counterparts, is vital for understanding potential barriers to exercise and informing exercise prescription.

Question (4) was "How does recovery compare between conventional laboratory-based muscle damaging exercise and regular exercise activities of daily life? As discussed (section 1.4), there have been a limited number of investigations directly comparing the muscle damage response between modes of exercise and these have focused on the demands of competitive sport (15, 27, 101). Currently, little is known about how the muscle damage response compares between common exercise activities (e.g., an EC) and laboratory-based modes of exercise (e.g., DR) frequently used to induce muscle damage. This insight is important for ensuring the recovery needs of recreationally active induvial are properly understood. If no muscle damage is evident following conventional exercise activities, then strategies used to recover from damage will not be required.

Key gaps were previously identified (section 1.7.1) within the EIMD literature where research is required. An updated outline of these areas is presented following the inclusion of the research conducted in this thesis (Figure 8-1). An outline of the main aims and key findings within each section of this thesis are also presented (Table 8-1).

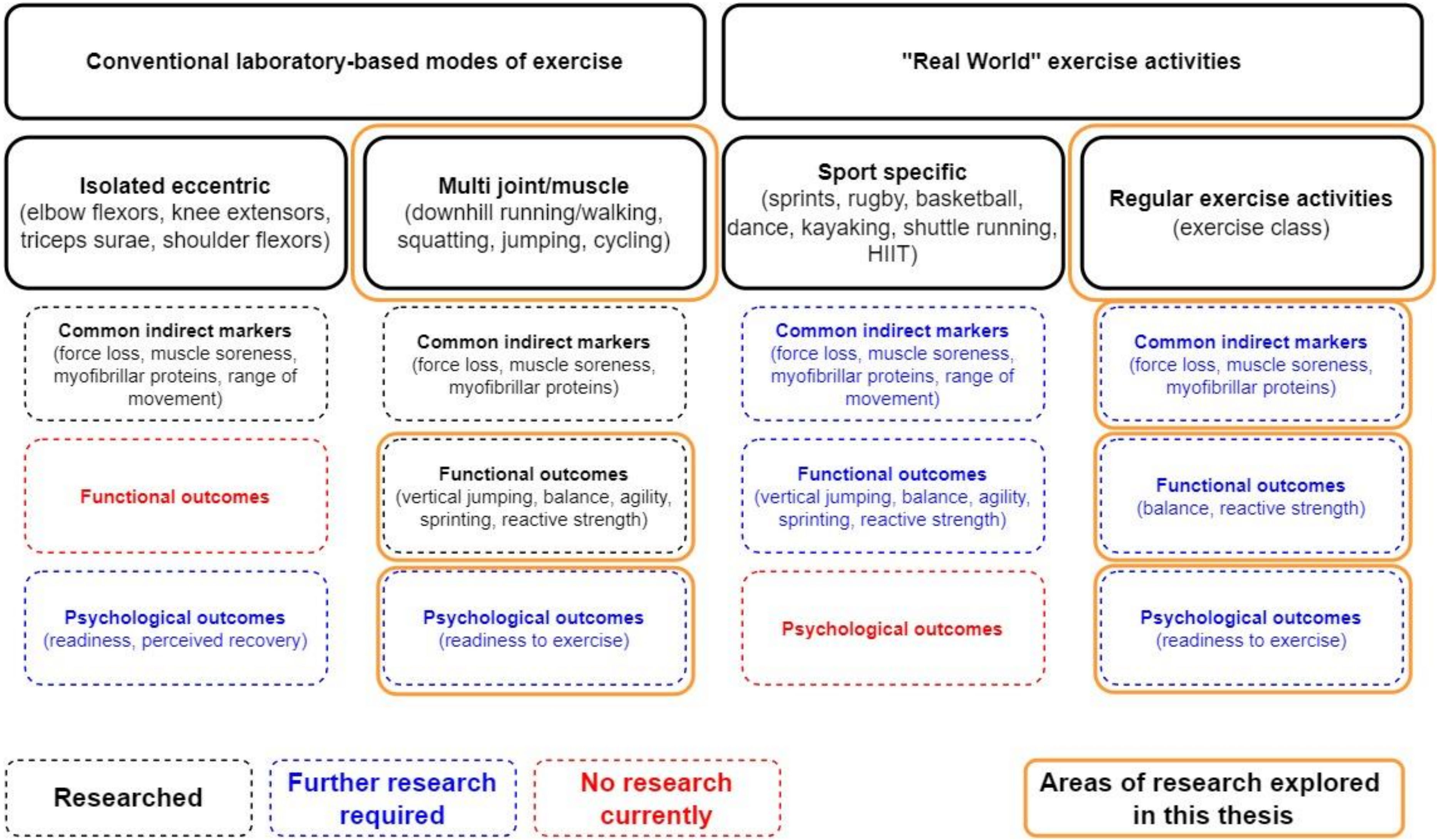


Figure 8-1. Outcomes to assess recovery from exercise-induced muscle damage and areas for further investigation.

Table 8-1. Outline of thesis chapter aims and key findings.

Chapter	Aims	Key Findings
3	• To investigate how the duration and severity of DR effect the muscle damage response	• All DR protocols resulted in muscle damage • The 30-minute protocol resulted in similar muscle damage in less time, while not requiring individuals to work at a greater intensity
4	• To investigate the impact of completing a conventional muscle damaging laboratory mode of exercise (DR) on functional and readiness to exercise outcomes • To determine if the responses of functional and readiness to exercise outcomes are associated with the response of common markers of muscle damage	• Functional capability and readiness to exercise impaired post exercise over the same period that muscle damage was evident • The change in functional and readiness to exercise outcomes is associated with the response of common indirect markers of muscle damage
5	• To investigate if completing a bodyweight EC causes muscle damage • To determine if functional and readiness to exercise outcome are affected following a bodyweight EC • To investigate the association between functional and readiness to exercise outcomes and indicators of muscle damage post a bodyweight EC	• Completing a bodyweight EC did not cause muscle damage • Reactive strength was impaired in the days following the EC, with balance remaining unaffected • The response of functional and readiness to exercise outcomes is more closely associated with the response of muscle soreness compared to other common indicators of muscle damage
6	• To determine if the muscle damage response is different following DR compared to a bodyweight EC • To investigate if functional and readiness to exercise outcomes are affected differently following DR compared to a bodyweight EC	• The conventional laboratory-based mode of exercise (DR) resulted in a greater muscle damage response • Balance ability was reduced post DR with no impairment evident after completing the EC • Both modes of exercise resulted in impairments in RS, with the response more prolonged following the EC • Readiness to exercise may be impaired to a greater extent to a greater extent following the DR compared to the EC
7	• To investigate muscle soreness following a bodyweight EC in active and inactive individuals • To determine if readiness to exercise is different between active and inactive individuals after completing a bodyweight EC	• The response of muscle soreness and readiness to exercise was similar for active and inactive individuals

Note: downhill running (DR); exercise class (EC)

8.2 Discussion

8.2.1. Conventional Muscle Damaging Exercise and Functional Outcomes

To investigate how functional outcomes were affected in the presence of EIMD, DR was identified and selected as an appropriate laboratory-based mode of exercise. This addressed a gap in the literature (Figure 8-1) where the impact of laboratory-based muscle damaging exercise (DR) on functional outcomes, had not been considered. As discussed (section 1.4), DR has been used extensively to investigate the time-course and recovery of EIMD. To understand how functional outcomes may be impaired by EIMD it was important to ensure the DR protocol employed would result in muscle damage. Within the literature it was unclear what the optimal DR conditions would be to ensure muscle damage occurred (26, 94, 111, 160, 161, 171, 172, 174-179, 186). To identify the appropriate time and severity of DR to cause muscle damage, three DR protocols were selected and compared (section 3). All three DR protocols resulted in muscle damage, however, the 30-minute protocol provided time saving benefits without requiring the individuals to work at a greater intensity. Therefore, the 30-minute DR protocol was selected and used to investigate responses following conventional laboratory-based muscle damaging exercise (DR) (section 4). When completed by recreationally active individuals, DR resulted in muscle damage, as evidenced by reduced force generating capacity and increased muscle soreness and myofibrillar proteins (CK) 24 h post exercise (Figure 4-2). This response was in line with observations previously reported within the literature (94, 111, 161, 175, 176, 180, 181, 183).

Over the same time period that muscle damage was apparent, impairments were observed in RS and balance ability (Figure 4-3). The impairment in balance ability following DR, supported previous research which identified reduced balance 24-48 h following muscle damaging sprint exercise (16). Therefore, it appears that when exercise is completed using the lower limbs which results in muscle damage (e.g., DR, sprints), balance ability is impaired when completing movements requiring the use of the lower body. The magnitude of the balance reduction observed following the DR could be impactful, as previously reduced balance has been associated with a greater risk of injury (142, 188). Therefore, completing muscle damaging exercise may leave individuals at a greater risk for injury in the days post exercise. This has implications for recovery and the selection of subsequent exercise activities. Individuals should be advised to avoid exercises requiring lower limb balance, after completing exercise which causes muscle damage in the legs, to reduce the risk they receive injury. “Split training” is a common approach used to vary training routines, where individuals train different body parts at each training session, to allow for muscle recovery and to maximise training load (213, 214). Split training could be advised after completing muscle damaging activities, allowing individuals to recover and focus on training unaffected muscle groups. Additionally, preconditioning exercise has been shown to attenuate the muscle damage response (49). Preconditioning with balance training may infer a similar protective effect on balance ability. Further research is required to determine how preconditioning may attenuate balance declines following muscle damaging exercise.

The observed reductions in RS following the DR were greater than those previously reported following muscle damaging sprints (15). Additionally, a greater impairment in force generating ability was evident following the DR compared to the previous research. This may suggest that the magnitude of force loss following muscle damaging exercise, is associated with the reduction of RS. Reduced RS in the days post completing muscle damaging exercise may have implications for athletic performance in subsequent exercise activities and increase the risk for injury (215). As discussed (section 2.2.5), RS is important for completing explosive exercise movements. Therefore, when exercising in the days post completing muscle damaging exercise, individuals should be advised to avoid activities requiring the rapid transition between concentric and eccentric phases of muscle action (e.g., jumping, changing direction), as this is likely to be impaired.

Less of an effect was evident on ROM post DR (Figure 4-3), with only a small to moderate decrease observed 24 h post exercise. Initially it was considered that this may be due to the location that was chosen for the ROM assessment, completed over the ankle joint using the weight bearing lunge test (see section 4.2.3.v). DR has been shown to result in muscle damage of both the knee flexors and plantar flexors (111). It would be expected that if damage had been caused at the plantar flexors an impairment would be observed when completing the weight bearing lunge. However, torque reduction has been shown to be greater in the knee flexors compared to the plantar flexors post DR (111). This may explain why only a small effect was evident on ROM post DR when assessed at the ankle joint. Two previous investigations have found ROM to be impaired following muscle damaging sprinting (16, 115). Due to the similar eccentric movements conducted during DR and the deceleration phase of the sprints, it was expected that DR would result in similar declines in ROM. Both sprinting studies assessed ROM using the knee joint, which requires the movement of the knee flexors (16, 115). Similar impairments in ROM may have been evident post DR had this been assessed at the knee joint. The weight bearing lunge test may lack the sensitivity required to detect changes at the ankle following DR. There are clear challenges in identifying an appropriate and reliable test, to assess ROM following muscle damaging exercise. It is suggested a battery of ROM measurements are required to properly assess ROM, such as the ROM-Sport, a field-based test which accurately assesses lower extremity ROM (216). Incorporating the ROM-sport to assess ROM following muscle damaging exercise, may more accurately monitor the ROM response. However, taking multiple measures is time consuming and may limit the practical application in sport and exercise settings.

The findings within this research following the DR (section 4.3.2), combined with the observations reported within the literature, demonstrate how functional assessments are emerging as additional indirect indicators of muscle damage (14-16, 27, 28, 62, 82, 83, 87, 101-103, 105, 115, 116). Understanding how functional capability is impaired by muscle damaging activities, assists in the appropriate selection of recovery strategies and subsequent exercise activities. Functional tests replicate the “real world” demands of exercise movements, involving multiple muscle groups (agonist/antagonist & synergistic). This may lead to impairments being identified which would be missed when assessing artificial single muscle assessments (i.e., isometric knee extensor force). Additionally, functional outcomes provide more practical value than conventional muscle damage markers, when identifying potential performance impairments or risk for injury. Incorporating a specific cluster of functional outcomes, may best indicate the recovery needs of an individual following muscle damaging exercise. For example, following DR, individuals should avoid exercise requiring balance and reactive strength and employ therapeutic strategies to address this recovery.

8.2.2. EIMD and Readiness to Exercise

Readiness to exercise was self-reported following DR to consider how this may be affected in response to muscle damaging exercise. This addressed an area within the literature where further research was required (Figure 8-1), to provide additional insight how psychological outcomes are affected following conventional muscle damaging exercise. As discussed (section 1.5.6), research into readiness to exercise in the presence of EIMD is limited. Additionally, the assessments used to assess readiness to exercise have been conducted using simple scales, at a limited number of assessment points (63, 71, 78).

A reduction in readiness to exercise (Figure 4-4) was evident for 1-2 days post completing muscle damaging exercise (DR; section 4.3.3). This suggests that if individuals complete an exercise activity which results in muscle damage, they will feel less ready to conduct further exercise. The reduced readiness to exercise post muscle damaging exercise, was predominantly detected across the subscales representing physical and overall constructs (PPC, MS, OR & OS). This suggests when assessing readiness to exercise, changes in these constructs should be monitored following muscle damaging exercise. The SRSS was designed to assess the current multidimensional recovery-stress state of an athlete, with the purpose of informing training load and identifying symptoms of overload (152-154). The SRSS was selected to monitor readiness to exercise, as a multidimensional assessment had not been previously used to monitor recovery from muscle damaging exercise and appeared the most appropriate outcome available. However, as responses were only observed on four subscales, the SRSS may need refining to only include physical and overall components of stress and recovery, for monitoring recovery from EIMD.

The change in the readiness to exercise was associated with the response observed in conventional indicators of muscle damage, being mostly strongly associated with muscle soreness (Table 4-3). This is understandable as muscle soreness was self-reported using a visual scale, which may suggest the mechanisms responsible for increased soreness are also associated with feeling less ready to exercise. The magnitude of change in muscle soreness and readiness to exercise was greater than for force loss, the more reliable indicator of muscle damage. This suggests readiness to exercise is more sensitive to change and may not reflect the magnitude of muscle damage which has occurred. Additionally, as discussed (section 1.5.2), high responders to muscle damage report a greater muscle soreness response (39). Therefore, high responders to muscle damage may also report a greater response in readiness to exercise.

Understanding how self-reported recovery may be impaired facilitates a more holistic approach to recovery management. If an individual believes they are less ready to exercise, it is intuitive that this will have implications for their motivation to participate in exercise. Athletes are more accustomed to managing their exercise load and understanding when they require recovery. Additionally, athletes frequently have coaches who control training load and monitor recovery for them. This is not available to recreationally active individuals incorporating physical activity in their day-to-day lives. These individuals are less aware of how to appropriately manage their exercise load and subsequent recovery. The assessment of readiness to exercise could be included in common exercise environments (e.g., gym facilities) to highlight recovery needs and assist with managing training loads.

When considered alone, the change in readiness to exercise may not provide an indicator for muscle damage. However, if used in conjunction with other functional assessments, it may provide a more complete illustration of the overall recovery needs of an individual, while being more accessible in common sport and exercise settings. If readiness were to be impaired without a physical or functional decline being evident, this could be important for providing support and motivation to conduct further exercise (i.e., physically you are fine, you should exercise). Conversely, if readiness is impaired in conjunction with functional outcomes, recovery strategies may be advised involving specific exercises or rest, to reduce the risk of injury.

8.2.3. Conventional Muscle Damaging Exercise vs Regular Exercise Activities

As highlighted (section 1.4), in recent years there has been a shift away from investigating muscle damage following laboratory-based eccentrically biased exercise protocols, which are known to result in large amounts of muscle damage. Laboratory exercise protocols have historically been used as they provide an ideal environment for investigating how recovery strategies may be effective in enhancing recovery from muscle damaging exercise. The emerging research has considered the muscle damage response following activities which are representative of those regularly undertaken in sporting environments (14-16, 27, 28, 62, 81-83, 87, 101-103, 105, 115, 116). This focus is likely due to the desire to enhance recovery and increase performance in athletic populations. No research had considered how regular physical activity which is conducted by individuals in their day-to-day exercise schedules, may result in muscle damage. As discussed (section 5.1), EC activities are conducted by a large proportion of the UK adult population (198). Understanding the muscle damage response following an acute EC activity, provides insight into the day-to-day recovery needs of regular exercisers.

When recreationally active individuals completed a bodyweight EC it did not appear to cause muscle damage, with only a small increase in muscle soreness observed (Figure 5-2). Additionally, when compared to conventional laboratory-based exercise (DR), the EC results in significantly less muscle damage (Figure 6-1). This suggests that following an EC, individuals will not need to recover from muscle damage and that this response is different to that observed following a conventional muscle damaging mode of exercise (DR) (91, 94, 111). Therefore, recovery from EC activities is unlikely to require the same therapeutic interventions as used when recovering from EIMD (217).

In addition to the muscle damage response, it is important to consider how functional outcomes may be affected following common exercise activities and how this may influence the demands of recovery. When functional outcomes were compared between conventional muscle damaging (DR) and regular (EC) exercise activities (section 6.3.2), conflicting results were observed for balance ability and RS. There was significant difference in the response of balance ability between the DR and EC (Figure 6-1). Following the DR, a significant impairment in balance ability was observed, whereas following an EC no decline was apparent. In contrast to balance ability, RS was impaired following both modes of exercise. The decline in RS was more prolonged following the EC, suggesting this type of activity even had a greater effect on stretch-shortening muscle activity. Interestingly, this occurred without muscle damage being evident, highlighting how exercise may not need to result in muscle damage for RS to be impaired.

These finding have implications for how individuals are monitored and advised on recovery following EC activities. Although there may be no need for individuals to recover from muscle damage following an EC, the prolonged decline in RS would affect which exercise activities are most suitable to complete, in the days post exercise. Individuals with reduced RS should be advised to avoid activities involving explosive movements requiring rapid changes of directions, to avoid reduced performance and potential risk for injury. An EC is led by qualified instructor, in the days post completing a high intensity explosive workout, the instructor could advise individuals to avoid these types of activities for a few days, to allow adequate recovery to occur. As balance is maintained post exercise, individuals could be advised to focus on low intensity exercises which require dynamic postural control (e.g., yoga, Pilates, slow single-leg resistance activities) over this period (218, 219).

The impairments in a functional test (RS) without muscle damage appearing evident using conventional indicators (i.e., force loss, CK), present another potential benefit to using functional outcomes to monitor recovery from exercise. If recovery was monitored using only conventional indicators of muscle damage it would not have been apparent that specific exercise activities may be best avoided in the days post an EC. Functional tests frequently involve completing movements requiring the use of multiple muscles and / or joints (142, 144, 220). This may increase the likelihood that impairments are detected in contrast to when using a contrived test (e.g., isometric knee extension), which is limited to assessing a specific muscle group. Additionally, functional tests may be more accessible than the monitoring of conventional indicators of muscle damage. Practitioners frequently use functional performance tests, such as power, dynamic balance and RS, to identify injury risk and assess return to sport criteria (17-19, 22). Although these outcomes can require specialised equipment to be performed, this comes at a much lower cost than outcomes requiring laboratory-based equipment, such as a force plate or isokinetic dynamometer. Additionally, as return to sport is assessed with athletes in sport and exercise facilities. It is more likely recreationally active individuals would be able to gain access to these outcomes to monitor recovery in gyms and leisure facilities.

When considering how readiness to exercise was affected following the DR (Figure 4-4) and EC (Figure 5-4), both activities resulted in individuals feeling less ready for 24-28 h. However, the reduced readiness was greater following the DR, the exercise which resulted in muscle damage. As discussed, (section 8.3), it appears the magnitude of muscle soreness may be associated with readiness to exercise post exercise. This may explain why DR caused a greater reduction in readiness to exercise compared to the EC. However, without muscle damage being evident, individuals still reported muscle soreness and feeling less ready to exercise following the EC. Therefore, after completing regular exercise activities which do not cause muscle damage, individuals may have symptoms (i.e., soreness, feel sluggish/unmotivated) which reduce the desire to exercise on subsequent days. Providing recovery advice to individuals may address symptoms and increase motivation and adherence to complete further exercise safely.

Combing a specific cluster of assessments (i.e., functional & psychological), tailored to the exercise activity, may present a practical approach to understanding and monitoring the recovery needs of individuals following regular day-to-day exercise activities. The assessments would need to be simple and quick to complete and be interpretable by the everyday exerciser. In recent years, an app has been developed which can be installed on smart phones or tablets, to assess indices of vertical jumping (196, 197). This allows for RS or leg power to be easily assessed and included in day-to-day exercise training routines. A combination of quickly assessable functional outcomes (i.e., power, balance, RS) and self-report measures (i.e., soreness, readiness) could be combined to allow individuals to assess what activities they should be completing. It may be possible to develop an additional software app, where a combination of test scores is entered and then recommendations provided on suitable exercise activities and advice on appropriate recovery. Research would be required to develop this and further refine functional and self-report assessments for regular use in leisure facilities.

8.2.4. Recovery in Physically Active and Inactive Individuals

Inactive individuals present another population of interest when investigating muscle damage and recovery from regular exercise activities. There is a need to increase physical activity levels in modern society and any insight into potential barriers to exercise could be beneficial (206). As discussed previously (section 1.6.1), completing an exercise bout provides a subsequent protective effect against muscle damage from similar future activities (RBE) (3-5). Individuals who do not regularly participate in physical activity are likely to lack this protective effect compared to individuals who regularly take part in exercise. Therefore, these inactive individuals may have a more severe response to common exercise stimuli and may recover from this differently. Insight into how inactive individuals respond and recover from exercise could aid in addressing potential barriers to exercise and increase their adherence to regular exercise.

As highlighted (section7.1), there has been limited research directly comparing muscle damage and recovery, between active and inactive individuals. Additionally, the inactive individuals included in this research have been unaccustomed to the mode of exercise, however, still reported to participate in regular sport/exercise each week. Therefore, the responses observed I these individuals are unlikely to reflect the who does not engage with physical activity. When compared, there was no difference in how physically active and inactive individuals, responded to and recovered from an EC (Figure 7-3 & Figure 7-4). Both conditions reported increased muscle soreness and muscular stress 24 h post exercise, which then began to subside. This suggests the recovery needs of individuals who exercise regularly and those who do not, are similar following and exercise class. This could have implications for the advice that is provided to individuals when they look to begin participating in physical activity.

The current UK physical activity guidelines advise on the type and amount of exercise that should be completed; however, they do not provide advice on strategies to continue to engage individuals with physical activity (187). The American College of Sports Medicine acknowledge there is limited data on why individuals do not maintain exercise behaviour (221). Individuals who engage regularly with physical activity are accustomed to feelings of soreness and fatigue and this does not discourage them from further exercise, however, non-exercisers may be discouraged by this. There is evidence that suggests support from experienced exercise leads, can influence adherence to exercise in sedentary individuals (221, 222). If exercise professionals inform individuals that the soreness and reduced readiness they experience following an EC is normal and similar for regular exercise attendees, this may provide a form of support and increase adherence to future exercise sessions. There is a clear need for further investigation into factors that may influence adherence to subsequent exercise sessions, in individuals beginning to engage in physical activity. Understanding why individuals do not continue to adhere with exercise is vital for increasing population levels of physical activity.

It appeared physically inactive individuals exerted themselves more and were more fatigued after completing the EC, compared to those who exercised regularly. Therefore, caution should be taken when interpreting these findings, as it was not possible monitor the exercise which took place during the EC in this research. Additional investigation is warranted, to determine if the observed responses occur when physically active and inactive individuals complete the same amount of work (volume, intensity, form), during an EC. If the amount of exercise completed is different between groups, this has implications for the design and prescription of workouts for those new to participating in physical activity.

8.2.5. Limitations & Future Research Directions

Several limitations and further research directions have been identified during the completion of this thesis and should be considered for future investigations.

i. Nutrition, Sleep & Exercise

Across the work presented in this thesis, there are some broader limitations which have the potential to influence the findings presented across the experimental chapters. There has been a large amount of research into how nutritional interventions may attenuate the symptoms of EIMD (217, 223, 224). There were no controls included across the investigations presented, to control for diet and supplement intake. Debate within the literature suggests reduced sleep may have an influence on athletic performance and physiological and cognitive outcomes (225, 226). No controls were included for sleep to ensure this did not influence the observed recovery from exercise. However, implementing these controls in the research may have altered the participants natural behaviour and not been representative of recovery in “real world” exercise settings.

As discussed (section 1.5.1), completing a previous bout of exercise can confer protection against subsequent similar exercise activities. Participants were screened to ensure they had not completed exercise that would be expected to confer protection against the subsequent exercise activity, within the previous six months (3-5). As the individuals involved across the investigations were considered recreationally active, they frequently engaged in common regular exercise activities (e.g., resistance training, aerobic exercise, team sports). It is possible some exercise activities conferred an unexpected protective effect which may have influenced any observed recovery from the DR and EC activities. However, this methodology was chosen to enable the responses to be representative of regular adult exercises within the general population

ii. Functional Assessments

The research completed in this thesis and focus within the literature, has primarily been using functional assessments completed with the lower limbs. Research should investigate if upper body functional outcomes are impaired similarly following muscle damaging activities. Additionally, the functional outcomes used in this research were mainly focused on balance ability and reactive strength. Investigations should explore a more diverse range of functional outcomes, which may have sport specific implications for performance or risk of injury (e.g., functional movement screens) (220).

iii. Recovery from Regular Exercise Activities

A bodyweight EC was used to investigate recovery from regular exercise in sections 5, 6 & 7. There are a variety of EC formats available to individuals and research should explore how the type of EC (i.e., bodyweight, with equipment, dance based) may influence the response to and recovery from exercise. Additionally, research should consider how responses to other regular exercise activities (e.g., gym-based resistance training) compare to those observed following an EC. This would provide insight into if exercise specific recovery advice is required.

iv. Repeated Bout Effect

The research within this thesis investigated acute responses to a single bout of exercise. Research should investigate how completing a subsequent similar bout of exercise, may confer protection against the impairments observed in functional and readiness to exercise outcomes.

v. Readiness to Exercise

The SRSS was chosen to monitor self-reported readiness to exercise, as this provided a more in-depth assessment than had been used within previous EIMD research. Research should expand on the utility of the SRSS in monitoring recovery from additional modes of exercise. Investigations should establish if the assessment of readiness to exercise can improve recovery and facilitate increased management of training loads, when incorporated into the training routines of recreationally active individuals. This may require the self-report measures to be further refined or used in combination with additional outcomes (i.e., muscle soreness), to produce a bespoke self-report assessment, which can accurately identify recovery demands.

vi. Recovery in Inactive Individuals

In the final investigation within this thesis (section 7), muscle soreness and readiness to exercise were used to monitor how physically active and inactive individuals, responded to and recovered from an EC. As it was not possible to include additional physical outcomes, future research should compare responses including conventional (i.e., force loss) and emerging indicators of muscle damage (i.e., power, balance, RS, agility). This would provide more insight into the potential differences between active and inactive individuals, when recovering from EC activities. Additionally, it is integral that future investigations control for the volume of exercise completed during the EC, to determine how this may influence the observed responses between active and inactive individuals during recovery.

8.3 Conclusion

The work completed in this thesis has addressed how the mode of exercise and environment in which it is conducted, influence the muscle damage response and recovery from exercise. The findings presented suggest that recovery from conventional laboratory-based muscle damaging exercise is more severe than recovery from a regular day-to-day exercise activity. Therefore, recovery strategies informed based on muscle damaging activities, are unlikely to be appropriate for assisting individuals in recovering from their regular exercise routine. Incorporating an appropriate cluster of assessments, including functional and self-reported outcomes, may better elucidate the complete recovery needs of an individual, while having the potential to be more accessible to all. Further research is required to support the initial findings presented here, which suggest individuals who do not regularly participate in exercise, recover similarly to their more active counterparts. This insight is vital for understanding barriers to exercise and may assist in addressing population levels of physical inactivity.

9. References

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10. Appendices

Appendix A Response of isometric force production following a single bout of muscle damaging exercise.

Reference	Author	Year	Exercise Protocol	Participants	Measurement Location	Pre-exercise Score	Findings
(71)	Abaidia et al.	2019	Eccentric Knee Flexion	10 male, soccer players	Knee	100 (%)	↓ at 0 (73), 20 (81), 48 (80) & 72 h (83)
(110)	Areces et al.	2015	Half Ironman	26 male, experienced triathletes	Whole body	1297 (N)	⇩ post-race (1104)
(79)	Black et al.	2015	Single Leg Split Squats	11 collegiate runners	Knee	266.8 (Nm)	⇩at 0 (200.7), 48 (196.6) & 96 h (232.0)
(35)	Bottas et al.	2011	Eccentric Elbow	10 male, healthy	Elbow	0 (%)	⇩at 0 (-18) & 48 h (-27)
(15)	Brown et al.	2016	Dance & Repeated Sprints	29 female, recreational dancers	Knee	Dance: 373.0 Sprints: 382.9 (N)	Dance: ⇩at 0 (335.7) & 24 (348.8) h Sprints: ⇩ at 0 (353.1), 24 (347.4) & 48 (351.0) h
(37)	Chapman et al.	2008	Eccentric Elbow	53 males, untrained	Elbow	62.9 (Nm)	⇩at 0 (37.0), 24 (38.1), 48 (40.6), 72 (44.3) & 96 h (46.4)
(98)	Eryılmaz et al.	2019	Repeated sprints	12 male, college athletes	Knee	250 (N)	⇩at 0 h (231)
(96)	Fernandes et al.	2019	Squats	27 male; young trained, middle-aged trained & middle-aged untrained	Knee	Young trained: 266 Middle-aged trained: 200 Middle-aged untrained: 212 (N)	Young-trained: Reduced at 24 (218) & 72 h (253) Middle-aged trained: Reduced at 24 (158) & 72 h (170) Middle-aged untrained: Reduced at 24 (164) & 72 h (172)
(40)	Fochi et al.	2016	Eccentric Elbow	12 male, untrained	Elbow	60°: 55.0 120°: 57.1 (Nm)	60°: ↓ at 24 (38.0), 48 (39.9), 72 (40.8) & 96 h (47.2) 120°: ↓ at 24 (48.9), 48 (49.8), 72 (47.7) & 72 H (53.5)
(72)	Heckel et al.	2019	Eccentric Knee	20 male, young & old	Knee	Young: 256 Old: 207 (Nm)	Young: ⇩at 24 (219), 48 (219) & 168 h (230) Old: ⇩at 24 (177), 48 (182) & 168 h (180)

Reference	Author	Year	Exercise Protocol	Participants	Measurement Location	Pre-exercise Score	Findings
(55)	Hicks et al.	2016	Eccentric Knee	22 (11 male), untrained	Knee	100 (%)	Male: ⇩ at 48 h (84.0) Female: ⇩ at 48 h (82.5)
(55)	Hicks et al.	2017	Eccentric Knee	16 male, recreationally active	Knee	264 (Nm)	⇩ at 48 h (221)
(56)	Hody et al.	2013	Eccentric Knee	18 male, sedentary, untrained	Knee	Dominant: 274.3 Nondominant: 262.2 (Nm)	Dominant: ⇩ at 24 h (229.2) Nondominant:⇩ at 24 h (228.0)
(99)	Howatson & Milak	2009	Repeated sprints	20 male, collegiate field sport players	Knee	100 (%)	⇩ at 24 (72.5) & 48 h (82.6)
(57)	Hunter et al.	2012	Eccentric Elbow	19 male, non-habitual weightlifters	Elbow	62.8 (Nm)	⇩ at 24 (40.2), 48 (42.2), 72 (44.8), 96 (47.6), 120 (53.6) & 144 (55.9) h
(16)	Khan et al.	2016	Repeated sprints	15 male, college football players	Knee	Quadriceps: 258.2 Hamstrings: 176.2 (#)	Quadriceps: ⇩ at 24 (209.6) & 48 h (215.4) Hamstrings: ⇩ at 24 (176.2) & 48 h (147.8)
(105)	Leeder et al.	2014	Loughborough Intermittent Shuttle Test	8 male, trained, rugby, hockey & football players	Knee	100 (%)	Reduced at 0 (86.4), 24 (93.3), 48 h (93.9)
(78)	Leite et al.	2019	Bilateral Shoulder Flexion	30 male, physically active	Shoulder	140.0 (N)	⇩ at 24 (108.2), 48 (110.5), 72 (115.7), 96 (118.8) & 168 h (126.4)
(93)	Maeo et al.	2016	Downhill walking	32 male, untrained	Knee	Constant: 230.9; Ramp: 220.3 (Nm)	Constant: ⇩ at 24 (180.1), 48 (184.5) & 72 h (196.2) Ramp: ⇨at any measurement point
(51)	Matta et al.	2019	Eccentric Elbow	11 male, untrained	Elbow	71.1 (Nm)	⇩ at 0 (44.5), 24 (48.1), 48 (49.4) & 72 h (50.3)
(73)	Nasrabadi et al.	2018	Leg Press	15 healthy male, untrained	Knee	530 (N)	⇩ at 0h (388)
(42)	Philippou et al.	2012	Eccentric Elbow	7 male, untrained	Elbow	290.2 (N)	⇩ 24 (156.6), 48 (185.1), 72 (198.3), & 96 h (221.7)

Reference	Author	Year	Exercise Protocol	Participants	Measurement Location	Pre-exercise Score	Findings
(43)	Piitulainen et al.	2010	Eccentric Elbow	9, healthy	Elbow	480 (N)	⇩ at 48 h (424)
(44)	Piitulainen et al.	2011	Eccentric Elbow	24 male, physically active	Elbow	318 (N)	⇩ at 0 h (227)
(45)	Plattner et al.	2011	Eccentric Elbow	32 male, untrained	Elbow	66.4 (Nm)	⇩ at 12 (42.1), 36 (43.1), 60 (48.1) & 84 h (47.6)
(46)	Radaelli et al.	2014	Eccentric Elbow	20 (10 male), untrained	Elbow	Male: 75.4 Female: 33.4 (Nm)	Male: ⇩ at 0 (55.3), 24 (67.4), 48 (68.6) & 72 h (67.0) Female: ⇩ at 0 (28.1), 24 (29.5), 48 (29.1) & 72 h (28.5)
(88)	Skurvydas et al.	2011	Drop Jumps	26 male, untrained	Elbow	100 (%)	50 Jumps: ⇩ at 0 (70), 72 (72) & 168 h (88) 100 Jumps: ⇩ at 0 (71), 72 (64), 168 (79) & 336 h (84)
(64)	Snieckus et al.	2013	Eccentric Knee	30 male, untrained (10), runners (10) & cyclists (10)	Knee	100 (%)	Untrained: ⇩ at 0 (67.7) & 48 h (80.3) Runners: ⇩ at 0 h (80.5) Cyclists: ⇩ at 0 h (76.4)
(47)	Starbuck & Eston	2012	Eccentric Elbow	15 male, untrained	Elbow	0 (%)	Ipsilateral: ↓ at 0 (-24.8), 24 (-22.3) & 48 h (-15.1) Contralateral: ↓ at 0 (-26.0), 24 (-27.1) & 48 h (-19.8)
(69)	Tsatlas et al.	2013	Eccentric Knee	19 female, moderately active	Knee	Extensors: 157.3 Flexors: 91.8 (Nm)	Extensors: ⇩ at 0 (119.3), 24 (95.0), 48 (88.9) & 72 h (102.9) Flexors: ⇩ at 0 (70.0), 24 (64.0), 48 (50.1) & 72 h (57.7)
(48)	Ye et al.	2015	Concentric and Eccentric Elbow	25 male	Elbow	455 (N)	⇩ at 0 h (323)

Note: ⇩ denotes significant decrease from pre-exercise ($p<0.05$); ⇨ denotes no significant change from pre-exercise ($p > 0.05$); ↓ denotes reduced but unclear if statistically significant from pre-exercise; # denotes that units of measurement were unclear; Where data values were not provided by authors estimates were extracted from figures (Graph Grabber v2.0.2, Henley-on-Thames, UK); Untrained individuals had not participated in exercise which would provide them with a protective effect against the exercise protocol in at least 3 months

Appendix B Response of muscle soreness following a single bout of muscle damaging exercise, assessed using a visual analogue scale.

Reference	Author	Year	Exercise Protocol	Participants	Scale	Pre-exercise Score	Findings
(71)	Abaidia et al.	2019	Eccentric Knee	10 male, soccer players	1 - 10	0.1	↑ at 0 (4.1), 20 (3.8), 48 (5.7) & 72 h (4.6)
(14)	Akdenzi et al.	2012	DJs	11 healthy male, football players	1 - 10	0.3	⇧ at 24 (6), 48 (9), 72 (7) & 96 h (3)
(79)	Black et al.	2015	Single Leg Split Squats	11 collegiate runners	0 – 100 (mm)	0.8	⇧ at 48 (58), 96 (30), 168 (10) & 240 h (4)
(35)	Bottas et al.	2011	Eccentric Elbow	10 male, healthy	0 – 100 (mm)	0	⇧ at 0h (4), 48 (30), 96 (25), 144 (10) & 192 h (3)
(15)	Brown et al.	2016	Dance & Repeated Sprints	29 female, recreational dancers	0 – 200 (mm)	Dance: 6 Sprints: 17	Dance: ⇧ at 0 (30), 24 (90) & 48 h (86) Sprints: ⇧ at 0 (48), 24 (88) & 48 (59) & 72 h (38)
(80)	Burt et al.	2012	Squats	10 male, untrained	0 - 10	0.4	⇧ at 24 (5.4) & 48 h (6.7)
(91)	Chrismas et al.	2017	Downhill Run	50 (14 female), physically active	0 – 100 (mm)	11	⇧ at 48 h (62)
(52)	Coratella & Bertinto.	2015	Isokinetic & Isoload Knee	30 male, healthy	0 – 100 (mm)	Isokinetic: 0.4 Isoload: 0.2	Isokinetic: ⇨ change at all time points Isoload: ⇧ at 24 (3.4), 48 (5.2), 72 (5.4) & 96 h (4.7)
(39)	Damas et al.	2016	Eccentric Elbow	286 male	0 – 100 (mm)	Low Responders: 0 Moderate responders: 0 High Responders: 0	Low Responders: ⇧ at 24 (29), 48 (37), 72 (27), 96 (14) & 120 h (11) Moderate responders: ⇧ at 24 (37), 48 (45), 72 (38), 96 (22) & 120 h (11) High Responders: ⇧ at 24 (42), 48 (57), 72 (51), 96 (33) & 120 h (19)
(28)	Doma et al.	2016	Basketball Training Session	10 female, elite basketball players	0 - 10	General: 2.7 Lower Body: 2.1	General: ⇧ at 24 h (5.6) Lower Body: ⇧ at 24 h (4.2)
(40)	Fochi et al.	2016	Eccentric Elbow	12 male, untrained	0 – 100 (mm)	60°: 0 120°: 0	60°: ↑ at 24 (4), 48 (5), 72 (2) & 96 h (1) 120°: ↑ at 24 (10), 48 (14), 72 (8) & 96 h (3)

Reference	Author	Year	Exercise Protocol	Participants	Scale	Pre-exercise Score	Findings
(41)	Hasenoehrl et al.	2017	Eccentric Elbow	16 male,	0 – 100 (mm)	High Intensity: 0 Low Intensity: 0	High Intensity: ↑ at 24 (44), 48 (58), 72 (39) & 96 h (11) Low Intensity: ↑ at 24 (34), 48 (40), 72 (24) & 96 h (7)
(72)	Heckel et al.	2019	Eccentric Knee	20 male, young & old	0 – 100 (mm)	Young: 0 Old: 0	Young: ⇧ at 24 (21), 48 (15) & 196 h (3) Old: ⇧ at 24 (13), 48 (12) & 196 h (1)
(53)	Heales et al.	2018	Eccentric Knee	13 (7 female), healthy	0 - 100	0	↑ at o (3.5) & 48 h (10)
(83)	Highton et al.	2009	Maximal Vertical Jumps	12, recreationally active, untrained	0 - 10	0	⇧ AT 24 (6.1) & 48 H (6.1)
(56)	Hody et al.	2013	Eccentric Knee	18 male, sedentary, untrained	0 - 10	0	⇧ at 24 h (2.3)
(99)	Howatson & Milak	2009	Repeated sprints	20 male, collegiate field sport players	0-200 (mm)	0	⇧ at 24 (90), 48 (116) & 72 h (44)
(57)	Hunter et al.	2012	Eccentric Elbow	19 male, non-habitual weightlifters	0-400 (mm)	95	⇧ at 24 (176), 48 (211) & 72 h (211)
(84)	Jakeman & Eston.	2013	Drop Jumps	17 female, physically active	0 – 10 (cm)	0.5	⇧ at 24 (6.1), 48 (7.0) & 72 h (3.9)
(86)	Karasiak et al.	2018	Counter-Movement Jumps	9 male, cyclists	0 – 10 (cm)	0.6	⇧ at 48 h (5.2)
(100)	Keane et al.	2015	Repeated Sprints	11 female, field-sport athletes	0 – 200 (mm)	7	⇧ at 0 (27), 24 (47), 48 (52) & 72 h (34)
(16)	Khan et al.	2016	Repeated sprints	15 male, college football players	0 – 200 (mm)	0	Quadriceps: ⇧ at 24 (86), 48 (115) & 72 h (73) Hamstrings: ⇧ at 24 (58), 48 (81) & 72 h (48)
(105)	Leeder et al.	2014	Loughborough Intermittent Shuttle Test	8 male, trained, rugby, hockey & football players	0 – 200 (mm)	0	⇧ at 24 h (110)

Reference	Author	Year	Exercise Protocol	Participants	Scale	Pre-exercise Score	Findings
(59)	Macgregor et al.	2018	Eccentric Knee	14 male, recreationally active	0 – 200 (mm)	35	⇧ at 24 (60) & 48 h (63)
(93)	Maeo et al.	2016	Downhill walking	32 male, mildly active, untrained	0 – 100 (mm)	0	Constant: ⇧ at 24 (45), 48 (72) & 72 h (55) Ramp: ⇨ at all-time points
(107)	Oxendale et al.	2016	Rugby Match	17 male, rugby players	0 – 6 (7-point Likert)	0	⇧ at 12 (1.1) & 36 h (0.8)
(42)	Philippou et al.	2012	Eccentric Elbow	7 male, untrained	0 – 100 (mm)	0	⇧ at 24 (39), 48 (53), 72 (49) & 96 h (28)
(44)	Piitulainen et al.	2011	Eccentric Elbow	24 male, physically active	0 – 5 (cm)	0	Concentric: ⇧ at 24 (1.4) & 48 h (1.2) Eccentric: ⇧ at 0 (0.7), 24 (1.9), 48 (2.6), 72 (2.6), 96 (1.8), 120 (1.1) & 144 h (0.8)
(76)	Pincheira et al.	2018	Eccentric Shoulder	20 healthy (11 male), untrained	0 - 10	0	⇧ at 48 h (3.1)
(45)	Plattner et al.	2011	Eccentric Elbow	32 male, untrained	0 – 10 (cm)	0	⇧ at 12 (2.3), 26 (3.8), 60 (3.3) & 84 (2.7) & 108 h (2.0)
(46)	Radaelli et al.	2014	Eccentric Elbow	20 (10 male), untrained	0 – 100 (mm)	0	Males: ⇧ at 24 (36), 48 (50) & 72 h (26) Females: ⇧ at 24 (36) & 48 h (24)
(63)	Rose Chrismas et al.	2017	Eccentric Knee	20 male, physically active	0 – 100 (mm)	2	⇧ post-exercise (42)
(87)	Sarabon et al.	2013	Drop Jumps followed by Bi-Lateral Leg Curls	11 healthy	0 – 10 (cm)	0.1	⇧ at 24 (4.4), 48 (4.7), 72 (3.1), 96 (0.8) & 120 h (0.4)
(65)	Souron et al.	2018	Concentric or Eccentric Knee	12 male, physically active	0 – 100 (mm)	0	Concentric: ⇨ at all-time points Eccentric: ⇨ at all-time points
(47)	Starbuck & Eston	2012	Eccentric Elbow	15 male, untrained	0 – 100 (mm)	0	↑ at 0 (21), 24 (39) & 48 h (33)
(67)	Tekus et al.	2017	Eccentric Knee	18 male; untrained & moderately trained	0 - 10	Moderately trained: 0.4 Untrained: 0.7	Moderately trained: ↑ at 24 h (3.2) Untrained: ↑ at 24 h (3.8)

Reference	Author	Year	Exercise Protocol	Participants	Scale	Pre-exercise Score	Findings
(68)	Torres et al.	2010	Eccentric Knee	14 male, untrained	0 – 10 (cm)	0	⇧ at 24 (2.3), 48 (3.9), 72 (1.8) & 96 h (0.6)
(69)	Tsatlas et al.	2013	Knee Extension & Flexion	19 female, moderately active	0 - 10	0	Extensors: ⇧ at 24 (5.2), 48 (7.3) & 72 h (6.3) Flexors: ⇧ at 24 (5.0), 48 (7.5) & 72 h (6.6)
(70)	Tseng et al.	2016	Eccentric Knee	26 male, untrained	0 – 100 (mm)	0	⇨ at all-time points
(89)	Twist & Eston.	2009	Vertical Jumps	7, physically active, untrained	0 - 10	0.5	⇧ at 48 h (6.6)
(103)	Twist & Sykes	2011	Simulated Rugby Match	10 male, rugby players	0 - 10	2.4	↑ at 24 (4.2) & 48 h (3.9)
(101)	Wiewelhove et al.	2015	High Intensity Interval Training	16 male, well trained	0 – 100 (mm)	0	⇧ at 24 h (3)

Note: ⇩ denotes significant decrease from pre-exercise ($p<0.05$); ⇨ denotes no significant change from pre-exercise ($p > 0.05$); ↓ denotes reduced but unclear if statistically significant from pre-exercise; Where data values were not provided by authors estimates were extracted from figures (Graph Grabber v2.0.2, Henley-on-Thames, UK); Untrained individuals had not participated in exercise which would provide them with a protective effect against the exercise protocol in at least 3 months

Appendix C Creatine Kinase response following a single bout of muscle damaging exercise.

Reference	Author	Year	Exercise Protocol	Participants	Findings
(110)	Areces et al.	2015	Half Ironman	26 male, experienced triathletes	⇧ post-race (808 v 173)
(94)	Baumann et al.	2014	Downhill Run	11 male, recreationally active	⇧ at 48 h
(35)	Bottas et al.	2011	Eccentric Elbow	10 male, healthy	⇧ at 96, 144 & 192 h
(82)	Bridgeman et al.	2017	Loaded Drop Jumps	8 male, resistance trained	↑ at 24 h
(37)	Chapman et al.	2008	Eccentric Elbow	53 males, untrained	⇧ at 24, 48, 72 & 96 h
(25)	Chen et al.	2011	Eccentric Elbow & Knee	17 sedentary	↑ at 24, 48, 72, 96 & 120 h
(38)	Chen et al.	2018	Eccentric Elbow	78 male, sedentary	↑ at 24, 48, 72, 96 & 120 h
(52)	Coratella & Bertinto.	2015	Isokinetic & Isoload Knee	30 male, healthy	Isokinetic: ⇨ at 24, 48, 72 & 96 h Isoload: ⇧ at 24, 48, 72 & 96 h
(39)	Damas et al.	2016	Eccentric Elbow	286 male	Low Responders: ⇧ at 48 h Moderate Responders: ⇧ at 48, 72, 96 & 120 h High Responders: ⇧ at 48, 72, 96 & 120 h
(106)	Devrnja & Matkovic	2018	Football Match	43 male, football players	⇧ post-game
(28)	Doma et al.	2016	Basketball Training Session	10 female, elite basketball players	⇧ at 24 h (318 vs 146)
(41)	Hasenoehrl et al.	2017	Eccentric Elbow	16 male,	Low Intensity: ↑ at 48, 72 & 96 h High Intensity: ↑ at 24, 48, 72 & 96 h
(53)	Heales et al.	2018	Eccentric Knee	13 (7 female), healthy	↑ at 48 h (178 vs 93)
(55)	Hicks et al.	2016	Eccentric Knee	22 (11 male), untrained	Males: ⇧ at 1, 48, 96 & 168 h Females: ⇨ at 48, 96 & 168 h
(55)	Hicks et al.	2017	Eccentric Knee	16 male, recreationally active	⇧ at 48, 96 & 168 h
(56)	Hody et al.	2013	Eccentric Knee	18 male, sedentary, untrained	Dominant: ⇧ 24 h Non-Dominant: ⇧ 24 h
(99)	Howatson & Milak	2009	Repeated sprints	20 male, collegiate field-sport players	⇧ at 24, 48 & 72 h

Reference	Author	Year	Exercise Protocol	Participants	Findings
(57)	Hunter et al.	2012	Eccentric Elbow	19 male, non-habitual weightlifters	⇧ at 24, 72 & 144 h
(84)	Jakeman & Eston.	2013	Drop Jumps	17 female, physically active	⇧ at 24 & 48 h
(85)	Kamandulis et al.	2010	Drop Jumps	7 male, untrained	↑ at 24 h
(100)	Keane et al.	2015	Repeated Sprints	11 female, field-sport athletes	⇧ at 24, 48 & 72 h
(16)	Khan et al.	2016	Repeated sprints	15 male, college football players	⇧ at 24, 48 & 72 h
(105)	Leeder et al.	2014	Loughborough Intermittent Shuttle Test	8 male, trained, rugby, hockey & football players	↑ at 24, 48 & 72 h
(93)	Maeo et al.	2016	Downhill walking	32 male, untrained	↑ at 24, 48 & 72 h
(60)	Magal et al.	2010	Eccentric Knee	17 male, untrained	⇧ at 24 h
(61)	Molina & Denadai	2012	Eccentric Knee	12 male, physically active	⇧ at 24 & 48 h
(107)	Oxendale et al.	2016	Rugby Match	17 male, rugby players	⇧ at 12 & 36 h
(114)	Park & Lee	2015	Downhill Run	13 male, moderately trained	⇧ at 24 & 48 h
(45)	Plattner et al.	2011	Eccentric Elbow	32 male, untrained	⇧ at 108 & 132 h
(102)	Pliauga et al.	2015	Simulated Basketball Game	10 male, basketball players	⇧ at 24 & 48 h
(87)	Sarabon et al.	2013	Drop Jumps followed by Bi-lateral Leg Curls	11 healthy, untrained	⇧ at 48 h
(88)	Skurvydas et al.	2011	Drop Jumps	26 male, untrained	⇧ at 72 h
(64)	Snieckus et al.	2013	Eccentric Knee	30 male, untrained (10), runners (10) & cyclists (10)	⇧ at 48 h for all groups
(67)	Tekus et al.	2017	Eccentric Knee	18 male; untrained & moderately trained	⇧ at 24 h for both groups
(68)	Torres et al.	2010	Eccentric Knee	14 male, untrained	⇧ at 24, 48, 72 & 96 h

Reference	Author	Year	Exercise Protocol	Participants	Findings
(69)	Tsatlas et al.	2013	Eccentric Knee	19 female, moderately active	⇧ at 72 h (4100 vs 149)
(70)	Tseng et al.	2016	Eccentric Knee	26 male, untrained	⇧ at 24 & 48 h
(103)	Twist & Sykes	2011	Simulated Rugby Match	10 male, rugby players	⇧ at 24 h
(115)	Verma et al.	2016	Repeated Sprints	32 male college football, (16 control)	⇧ at 24, 48 & 72 h
(101)	Wiewelhove et al.	2015	High Intensity Interval Training	16 male, well trained	⇧ at 24 h
(90)	Zhou et al	2011	Vertical Jumps	13 male, sprinters, collegiate athletes	⇧ at 24, 48 & 72 h

Note: ⇧ denotes significant increase from pre-exercise ($p<0.05$); ⇨ denotes no significant change from pre-exercise ($p > 0.05$); ↑ denotes increased but unclear if statistically significant from pre-exercise; Untrained individuals had not participated in exercise which would provide them with a protective effect against the exercise protocol in at least 3 months

Appendix D Response of range of movement following a single bout of muscle damaging exercise.

Reference	Author	Year	Exercise Protocol	Participants	Measurement Protocol	Pre-exercise Score	Findings
(37)	Chapman et al.	2008	Eccentric Elbow	53 males, untrained	Elbow; Difference between FANG & RANG	132 (°)	⇩ at 0 (120), 24 (121), 48 (120), 72 (120) & 96 h (121)
(39)	Damas et al.	2016	Eccentric Elbow	286 male	Elbow; Difference between FANG & RANG	100 (%)	Low Responders: ⇩ at 0 (87), 24 (89), 48 (90), 72 (92) & 96 h (93) Moderate Responders: ⇩ at 0 (83), 24 (82), 48 (82), 72 (86), 96 (88) & 120 h (92) High Responders: ⇩ at 0 (79), 24 (76), 48 (74), 72 (77), 96 (82) & 120 h (86)
(40)	Fochi et al.	2016	Eccentric Elbow	12 male, untrained	Elbow; Difference between FANG & RANG	0 (°)	60°: ↓ at 24 (-3), 48 (-3) & 72 h (-1) 120°: ↓ at 24 (8), 48 (8), 72 (8) & 96 h (7)
(16)	Khan et al.	2016	Repeated sprints	15 male, college football players	Knee Flexion	132 (#)	⇩ at 24 (124) & 48 h (128)
(62)	Peñailillo et al.	2017	Eccentric Cycling	8 male, untrained	Active Knee Extension	-22 (°)	⇩ at 0 (-30), 24 (-35), 48 (-35) & 72 h (-28)
(42)	Philippou et al.	2012	Eccentric Elbow	7 male, untrained	Elbow; Difference between FANG & RANG	1.28 (rad)	⇩ at 24 (0.97) & 48 h (0.90)
(45)	Plattner et al.	2011	Eccentric Elbow	32 male, untrained	Elbow; Resting Angle	0 (°)	⇩ at 12 (10), 36 (11), 60 (9) & 84 h (8)
(47)	Starbuck & Eston	2012	Eccentric Elbow	15 male, untrained	Elbow; Resting Angle	0 (%)	↓ at 0 (-3), 24 (-7) & 48 h (-4)
(70)	Tseng et al.	2016	Eccentric Knee	26 male, untrained	Knee; Difference between FANG & RANG	113 (°)	⇩ at 0 (107), 24 (109) & 48 h (110)
(115)	Verma et al.	2016	Repeated Sprints	32 male college football, (16 control)	Knee Flexion	134 (°)	⇩ at 24 (117), 48 (125) & 72 h (130)

Note: ⇩ denotes significant decrease from pre-exercise ($p<0.05$); ↓ denotes reduced but unclear if statistically significant from pre-exercise; # denotes that units of measurement were unclear; Where data values were not provided by authors estimates were extracted from figures (Graph Grabber v2.0.2, Henley-on-Thames, UK); Untrained individuals had not participated in exercise which would provide them with a protective effect against the exercise protocol in at least 3 months

Appendix E Response of functional outcomes following a single bout of muscle damaging exercise.

Reference	Author	Year	Exercise Protocol	Participants	Measure(s)	Pre-exercise Score	Findings
(14)	Akdenzi et al.	2012	DJs	11 male, football players	Agility (Illinois), Sprint time (30m)	Agility (s): 16.8 Sprint (s): 5.5	Agility: ⇧ at 0 (18.5), 24 (19.7) & 48 h (19.1) Sprint time: ⇧ at 0 (6.0), 24 (6.3) & 48 h (6.0)
(82)	Bridgeman et al.	2017	Eccentric loaded DJs	8 male, resistance trained	CMJ, SJ	CMJ (cm): 47.52 SJ (cm): 43.67	CMJ: ↓ at 0 (45.15) & 24 h (46.49) SJ: ↓ at 0 h (41.92)
(15)	Brown et al.	2016	Dance & Repeated Sprints	29 female, recreational dancers	CMJ, RSI	CMJ (cm): 26.3 (dance), 27.0 (sprints) RSI ($cm.s^{-1}$)	CMJ: ⇩ at 0 h following dance (24.4) and sprints (22.3); ⇩ at 24 (24.1) & 48 h (24.4) following sprints RSI: ⇩at 0 h following sprints (61.3)
(81)	Dabbs & Chandler	2018	Bulgarian Split Squats	13 (5 male), resistance trained	Balance; static & dynamic (Biodex)	Static (sway): 0.35 Dynamic (sway): 1.38	Static: ⇨ change at all time points Dynamic: ⇨ change at all time points
(28)	Doma et al.	2016	Basketball Training Session	10 female, basketball players	CMJ, change of direction (COD), suicide test (ST)	CMJ (m): 0.50 COD (s): 5.92 ST (s): 29.9	CMJ: ⇨ all time points COD: ⇨ all time points ST: ⇧ at 24 h (30.5)
(83)	Highton et al.	2009	Maximal Vertical Jumps	12 healthy, recreationally active, untrained	Sprint time (10m), Agility (Agility-505)	Sprint (s): 1.97 Agility (s): 2.41	Sprint: ⇧ at 24 (2.08) & 48 h (2.08) Agility: ⇧ at 24 (2.54) & 48 h (2.63)
(16)	Khan et al.	2016	Repeated sprints	15 male, college football	CMJ, SJ, Sprint time (20m), Balance; static (Stork) & dynamic (Y-balance)	CMJ (cm): 47.3 SJ (cm): 42.8 Sprint (s): 3.4 Static balance (s): 47.7 Dynamic balance (%): 79.8 (ANT), 102.0 (PL), 99.2 (PM)	CMJ: ⇩ at 24 (41.8) & 48 h (42.0) SJ: ⇩ at 24 (39.3 & 48 h (39.7) Sprint: ⇧ at 24 (3.7) and 48 h (3.6) Static balance: ⇩ at 24 h (25.2) Dynamic balance: ⇩ at 24 (ANT 74.2; PL 95.2; PM 89.1) & 48 h (ANT 74.5; PL 96.6; PM 91.2)
(105)	Leeder et al.	2014	Loughborough Intermittent Shuttle Test	8 male, trained, rugby, hockey & football players	CMJ	CMJ (cm): 36.0	CMJ: ⇩ at 24 h (33.6)

Appendix F Response of self-reported perceived recovery / readiness following a single bout of muscle damaging exercise.

Reference	Author	Year	Exercise Protocol	Participants	Measure	Pre-exercise Score	Findings
(71)	Abaidia et al.	2019	Eccentric Knee	10 male, football players	Perceived recovery (0-10); lower score = more recovered	Not provided	↑ at 48 (6.0) & 72 h (5.1) compared to 20 h (3.5) post-exercise.
(78)	Leite et al.	2019	Bilateral Shoulder Flexion	30 male, physically active	Perceived recovery (TQR scale); higher score = more recovered	18 (6-20)	⇩ at 24 (11), 28 (13) & 72 h (15)
(63)	Rose Chrismas et al.	2017	Eccentric Knee	20 male, physically active	Readiness; higher score = increased readiness	92 (1-100)	⇩post-exercise (75)

Note: Total quality recovery (TQR); ⇩ denotes significant decrease from pre-exercise ($p<0.05$); ↑ denotes reduced but unclear if statistically significant from pre-exercise; Where data values were not provided by authors estimates were extracted from figures (Graph Grabber v2.0.2, Henley-on-Thames, UK);

Appendix G - Short Recovery & Stress Scale (SRSS)

Name/Code	Date/Time

Short Recovery Scale

Below you find a list of expressions that describe different aspects of your current state of recovery. Rate how you feel **right now** in relation to your best ever recovery state.

		0	1	2	3	4	5	6	
Physical Performance Capability *e.g. strong, physically capable, energetic, full of power*	does not apply at all	○	○	○	○	○	○	○	fully applies
Mental Performance Capability *e.g. attentive, receptive, concentrated, mentally alert*	does not apply at all	○	○	○	○	○	○	○	fully applies
Emotional Balance *e.g. pleased, stable, in a good mood, having everything under control*	does not apply at all	○	○	○	○	○	○	○	fully applies
Overall Recovery *e.g. recovered, rested, muscle relaxation, physically relaxed*	does not apply at all	○	○	○	○	○	○	○	fully applies

Short Stress Scale

Below you find a list of expressions that describe different aspects of your current state of stress. Rate how you feel **right now** in relation to your highest ever stress state.

		0	1	2	3	4	5	6	
Muscular Stress *e.g. muscle exhaustion, muscle fatigue, muscle soreness, muscle stiffness*	does not apply at all	○	○	○	○	○	○	○	fully applies
Lack of Activation *e.g. unmotivated, sluggish, unenthusiastic, lacking energy*	does not apply at all	○	○	○	○	○	○	○	fully applies
Negative Emotional State *e.g. feeling down, stressed, annoyed, short-tempered*	does not apply at all	○	○	○	○	○	○	○	fully applies
Overall Stress *e.g. tired, worn-out, overloaded, physically exhausted*	does not apply at all	○	○	○	○	○	○	○	fully applies

Appendix H – Physical Activity Readiness Questionnaire

Physical Activity Readiness Questionnaire - PAR-Q (revised 2002)

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO	
☐	☐	**1. Has your doctor ever said that you have a heart condition and that you should only do physical activity recommended by a doctor?**
☐	☐	**2. Do you feel pain in your chest when you do physical activity?**
☐	☐	**3. In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4. Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5. Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6. Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7. Do you know of any other reason why you should not do physical activity?**

If you answered

YES to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programs are safe and helpful for you.

NO to all questions

If you answered NO honestly to all PAR-Q questions, you can be reasonably sure that you can:

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

DELAY BECOMING MUCH MORE ACTIVE:

- if you are not feeling well because of a temporary illness such as a cold or a fever – wait until you feel better; or
- if you are or may be pregnant – talk to your doctor before you start becoming more active.

PLEASE NOTE: If your health changes so that you then answer YES to any of the above questions, tell your fitness or health professional. Ask whether you should change your physical activity plan.

Informed Use of the PAR-Q: The Canadian Society for Exercise Physiology, Health Canada, and their agents assume no liability for persons who undertake physical activity, and if in doubt after completing this questionnaire, consult your doctor prior to physical activity.

No changes permitted. You are encouraged to photocopy the PAR-Q but only if you use the entire form.

NOTE: If the PAR-Q is being given to a person before he or she participates in a physical activity program or a fitness appraisal, this section may be used for legal or administrative purposes.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

NAME ____

SIGNATURE ____ DATE ________________________________

SIGNATURE OF PARENT ________________________________ WITNESS ________________________________
or GUARDIAN (for participants under the age of majority)

Note: This physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if your condition changes so that you would answer YES to any of the seven questions.

1:12

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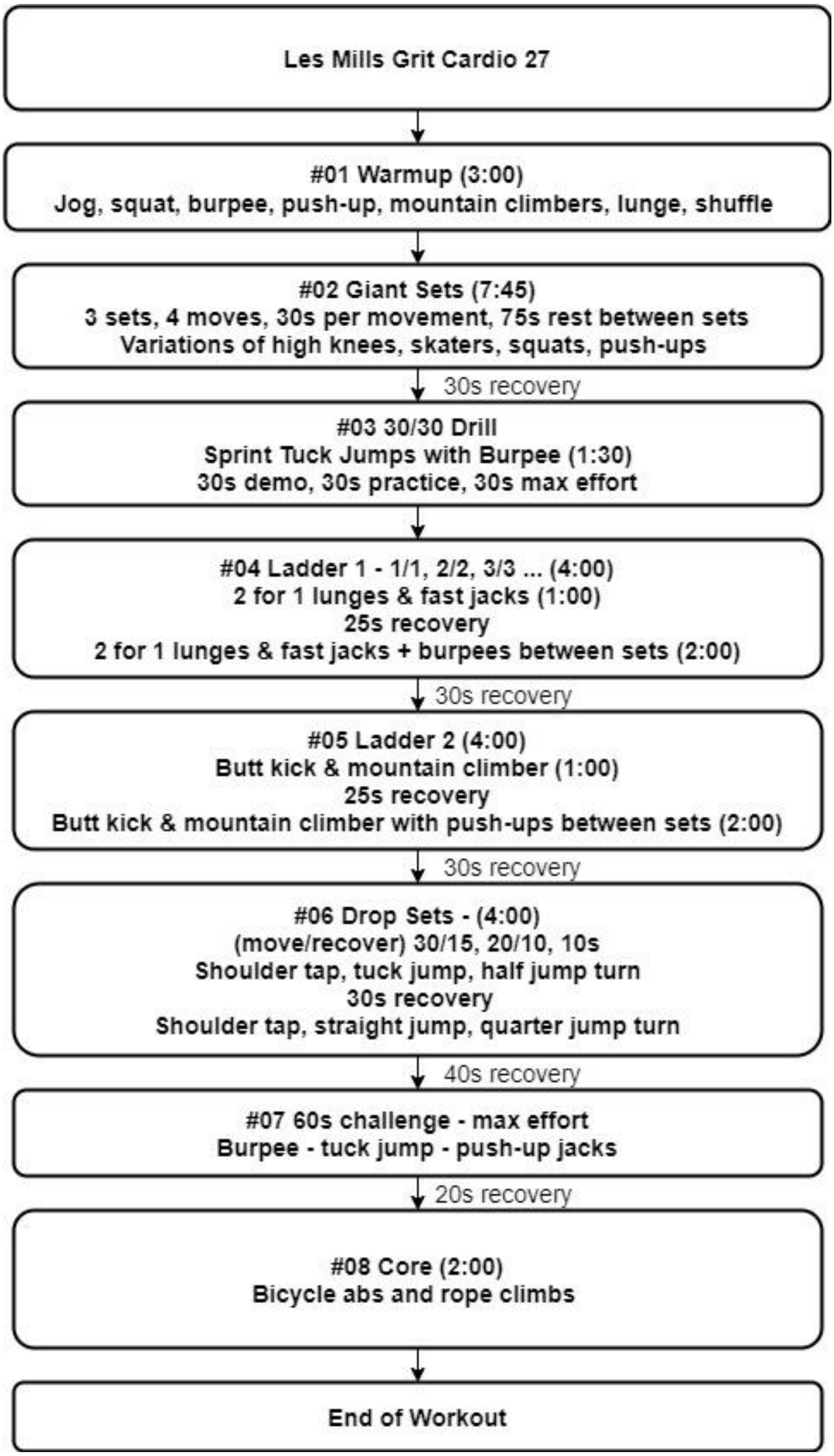
Appendix I Descriptive statistics (mean ± SD) for all measures across both conditions, at all-time points, following downhill running.

Time	Group	Isometric Force (N)	Creatine Kinase ($U.L^{-1}$)	Muscle Soreness (mm)	Balance (%)	Reactive Strength Ratio	Range of Movement (°)	Readiness to Exercise (0 - 6)							
								PPC	MPC	EB	OR	MS	LOA	NES	OS
Pre	Control	756 ± 355	-	3.2 ± 3.3	86.6 ±15.5	2.08 ± 0.79	-	4.8 ± 1.3	5.3 ± 1.0	5.5 ± 1	5.5 ± 1.1	1.0 ± 1.4	1.3 ± 1.0	1.3 ± 1.5	1.5 ± 2.4
	Experimental	856 ± 190	155 ± 63	6.6 ± 5.2	93.2 ± 5.3	2.07 ± 0.42	34.3 ± 6.1	5.6 ± 1.3	6.1 ± 0.8	5.8 ± 1.1	5.5 ± 1.2	2.4 ± 1.6	2.0 ± 1.3	2.2 ± 1.7	2.1 ± 1.2
Post	Control	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Experimental	693 ± 1.28	-	-	-	-	-	-	-	-	-	-	-	-	-
24 h	Control		-		88.1 ± 14.4	2.02 ± 0.85	-	5.3 ± 1.0	5.5 ± 0.6	5.5 ± 1.0	5.3 ± 1.0	1.0 ± 1.4	0.5 ± 0.6	0.3 ± 0.5	0.8 ± 1.0
	Experimental	751 ± 212	421 ± 132	28.2 ± 20.1	89.7 ± 7.5	1.85 ± 0.43	32.1 ± 6.2	4.0 ± 1.8	5.4 ± 1.3	5.6 ± 1.0	3.3 ± 1.8	2.3 ± 1.7	2.9 ± 1.7	2.3 ± 1.6	3.4 ± 1.6
48 h	Control		-		87.6 ± 14.6	2.15 ± 0.98	-	4.8 ± 1.3	5.0 ± 1.4	5.3 ± 1.5	4.8 ± 1.9	1.0 ± 0.8	1.0 ± 1.4	0.5 ± 1.0	0.8 ± 1.5
	Experimental	754 ± 216	248 ± 46	22.1 ± 17.1	91.6 ± 7.3	1.95 ± 0.48	33.6 ± 7.6	4.3 ± 2.0	5.7 ± 1.2	5.4 ± 1.3	3.9 ± 2.0	4.0 ± 2.0	2.8 ± 1.5	2.1 ± 1.2	2.8 ± 1.2
72 h	Control		-		88.9 ± 15.8	2.07 ± 0.94	-	5.0 ± 1.4	5.0 ± 1.4	5.3 ± 1.5	4.5 ± 1.3	1.3 ± 1.3	0.8 ± 1.0	0.5 ± 1.0	0.8 ± 1.0
	Experimental	780 ± 203	157 ± 50	8.8 ± 7.3	94.0 ± 6.2	1.96 ± 0.48	34.6 ± 7.1	5.5 ± 1.0	6.0 ± 0.9	5.8 ± 0.8	5.3 ± 0.8	2.9 ± 1.0	1.9 ± 1.0	2.0 ± 1.0	2.4 ± 1.2
96 h	Control		-		90.0 ± 14.3	2.07 ± 0.76	-	5.0 ± 1.4	5.3 ± 1.5	5.0 ± 2.0	4.8 ± 1.9	0.8 ± 1.0	0.8 ± 1.5	0.8 ± 1.5	1.0 ± 1.4
	Experimental	800 ± 230	154 ± 26	5.0 ± 4.1	95.8 ± 4.8	2.02 ± 0.47	35.8 ± 6.7	6.3 ± 0.8	6.6 ± 0.5	6.5 ± 0.5	6.0 ± 0.9	1.9 ±0.8	1.3 ± 0.7	1.3 ± 0.6	1.6 ± 0.5

Note: Control (n = 4), Experimental (n = 12 (n = 10 for Creatine Kinase)); Range of Movement measured at the ankle joint; Readiness to Exercise assessed using subscales of the Short Recovery and Stress Scale (SRSS): Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS)

Appendix J – Les Mills Grit Cardio 27

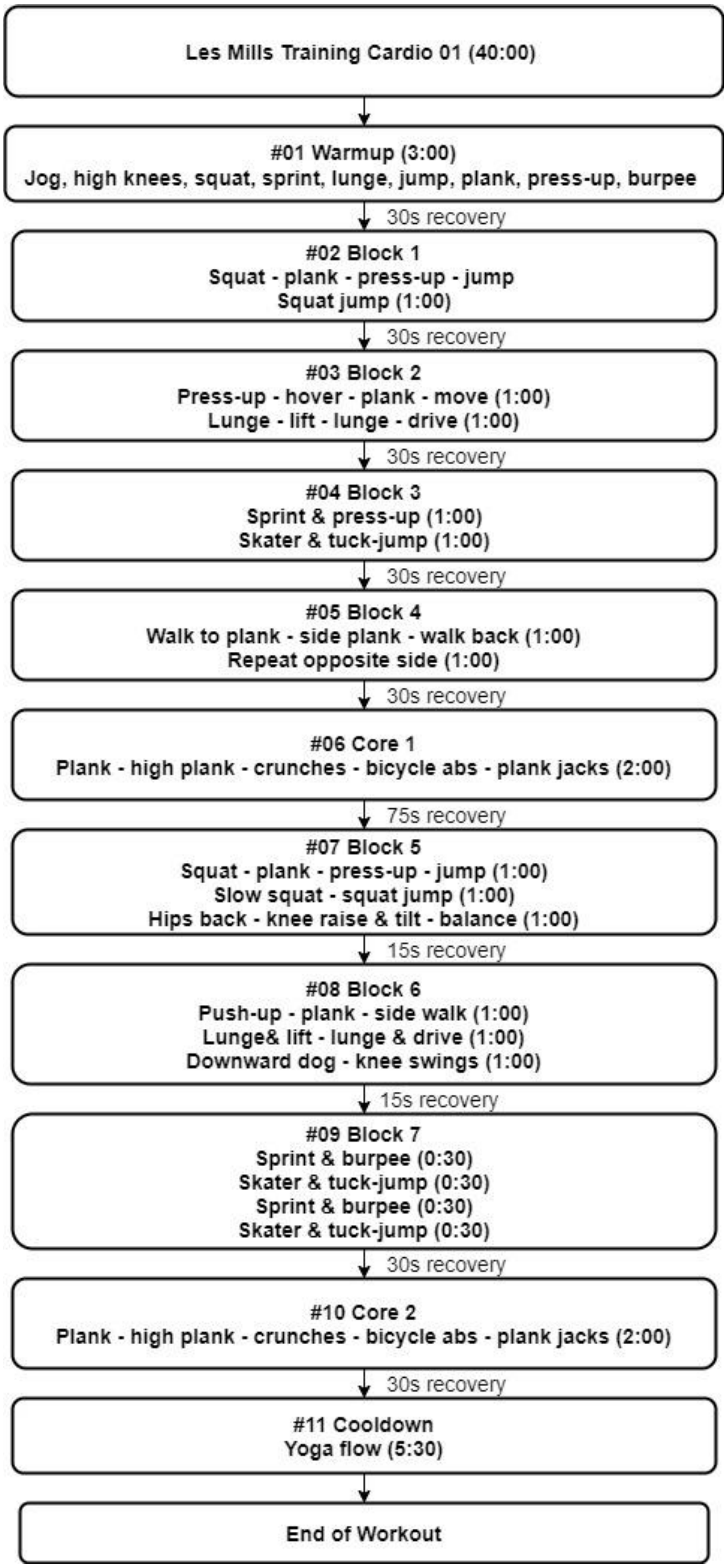


Appendix K Descriptive statistics (mean ± SD) for all measures, at all-time points, following a simulated exercise class (n = 15).

Time	Isometric Force (N)	Creatine Kinase (U.L^{-1})	Muscle Soreness (mm)	Balance (%)	Reactive Strength Ratio	Readiness to Exercise (0 - 6)							
						PPC	MPC	EB	OR	MS	LOA	NES	OS
Pre	724 ± 254	180.6 ± 54.9	4.1 ± 5.4	92.3 ± 9.1	2.06 ± 0.55	4.3 ± 1.2	4.3 ± 1.2	4.5 ± 1.4	4.1 ± 1.4	1.6 ± 1.1	1.6 ± 1.2	1.3 ± 1.0	1.4 ± 1.1
Post	639 ± 250	-	-	-	-	-	-	-	-	-	-	-	-
24 h	695 ± 247	230.3 ± 97.5	11.4 ± 11.1	92.1 ± 8.9	1.92 ± 0.58	3.7 ± 1.0	4.3 ±1.1	4.1 ± 1.1	2.9 ± 1.2	3.9 ±0.9	2.0 ± 1.0	1.7 ± 1.0	2.2 ± 1.2
48 h	714 ± 278	163.8 ± 60.4	8.6 ± 12.2	92.9 ± 9.6	1.83 ± 0.60	3.7 ± 1.3	4.3 ± 1.2	4.3 ± 1.0	3.3 ± 1.0	3.3 ± 1.5	2.0 ± 1.3	1.4 ± 1.0	2.0 ± 1.4
72 h	729 ± 270	141.8 ± 54.2	2.6 ± 3.5	94.9 ± 9.5	1.92 ± 0.57	4.9 ± 0.7	4.9 ± 0.9	5.0 ± 0.8	4.7 ± 0.7	1.5 ± 1.1	1.2 ± 0.8	1.1 ± 1.0	1.2 ± 0.9
96 h	720 ± 266	140.8 ± 56.9	1.9 ± 2.4	95.8 ± 9.4	1.92 ± 0.54	5.0 ± 0.9	4.9 ± 1.0	4.8 ± 1.2	5.2 ± 0.8	0.6 ± 0.6	1.3 ± 1.4	1.0 ± 1.1	1.2 ± 1.0

Note: Creatine Kinase (n = 8); Readiness to Exercise assessed using subscales of the Short Recovery and Stress Scale (SRSS): Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS)

Appendix L – Les Mills Training Cardio 01



Appendix M Descriptive statistics (mean ± SD) for all measures across both conditions, at all-time points, following a virtual exercise class.

Time	Group	Rating of Perceived Exertion (6 – 20)	Rating of Fatigue (0 – 10)	Muscle Soreness (mm)	Readiness to Exercise (0 - 6)							
					PPC	MPC	EB	OR	MS	LOA	NES	OS
Pre	Active	-	-	7.7	5.2 ± 1.1	5.4 ± 1.3	5.3 ± 1.2	5.2 ± 1.4	2.1 ± 0.9	3.1 ± 1.3	2.7 ± 1.4	3.2 ± 1.5
	Inactive	-	-	5.8 ± 5.2	3.8 ± 1.2	5.2 ± 0.9	5.2 ± 0.6	4.3 ± 1.5	2.7 ± 1.2	3.9 ± 1.6	3.1 ± 0.9	3.3 ± 1.4
Post	Active	6.8 ± 1.8	5.6 ± 2.3	-	-	-	-	-	-	-	-	-
	Inactive	7.6 ± 1.4	6.9 ± 1.4	-	-	-	-	-	-	-	-	-
24 h	Active	-	-	39.1 ± 19.5	4.5 ± 0.8	5.6 ± 1.0	5.7 ± 1.2	4.2 ± 1.3	4.5 ± 1.1	3.4 ± 1.4	2.6 ± 1.2	3.6 ± 1.3
	Inactive	-	-	35.0 ± 16.1	4.2 ± 1.1	5.0 ± 1.1	5.2 ± 0.8	3.9 ± 1.1	4.8 ± 0.8	3.2 ± 1.4	2.6 ± 1.2	2.6 ± 1.2
48 h	Active	-	-	20.3 ± 18.5	5.4 ± 0.8	5.8 ± 0.9	5.8 ± 1.2	5.2 ± 1.2	3.3 ± 1.5	2.5 ± 1.3	2.2 ± 1.1	2.2 ± 1.2
	Inactive	-	-	20.6 ± 24.4	4.8 ± 1.1	5.3 ± 1.3	5.7 ± 0.9	5.0 ± 1.3	3.7 ± 1.3	3.6 ± 1.3	2.4 ± 1.0	2.9 ± 1.2

Note: Active (n = 13), Inactive (n = 11); Readiness to Exercise assessed using subscales of the Short Recovery and Stress Scale (SRSS): Physical Performance Capability (PPC), Muscular Performance Capability (MPC), Emotional Balance (EB), Overall Recovery (OR), Muscular Stress (MS), Lack of Activation (LOA), Negative Emotional State (NES) and Overall Stress (OS)