Sprint Interval Training in Older Adults: Recovery, Acute Effects, and Training Adaptations

By

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Thesis Abstract

Rationale & Introduction:

Human ageing is presently characterised by an unavoidable biological ageing process following maturation, which occurs in the 2nd decade of life. Consequently, a decline in overall human functioning is observed. However, this process can be skewed to decelerate the ageing process and increase human functioning with the adoption of lifestyle changes. The focus of this thesis was to analyse the relevance of physical activity and its effects on markers of physical functioning and investigate the physiological and practical efficacy of high-intensity interval training (HIIT), and more specifically sprint interval training (SIT) as a method of improving physical functioning in ageing cohorts.

Studies Overview:

A systematic review meta-analysis was conducted with a focus on the physiological outcomes of HIIT interventions in older people. Study one investigated the peak power output recovery following 3 and 5 days of rest following SIT. Study two compared the physiological, psychological, and perceptive responses to SIT in three distinct modes: static sprinting, cycle ergometry, and box stepping. Study three investigated the effects of an 8 week SIT intervention in older adults on aerobic capacity, hemodynamics, and muscle power.

Results:

Systematic review meta-analysis) HIIT interventions were found to have a positive effect on aerobic capacity (standard difference in means [SDM] = 0.74)), muscle power (SDM = 1.13), muscle strength (SDM = 0.19), and lean body mass (SDM = 0.17), and a negative effect on body fat (SDM = -0.30). **Study 1)** The findings suggest that older individuals recover similarly between 3 and 5 five days of rest following SIT with a small effect (p = 0.702, n^2_p = 0.022).

Study 2) The findings of study two indicate that static sprinting and the cycle ergometer modes are likely more suitable to providing the physiological stimulus required to instigate adaptations to SIT. A medium effect of exercise mode for peak oxygen uptake ($V\dot{O}_{2peak}$) was observed (n^2=0.213, p=0.091), a large effect was observed for peak blood lactate (BLa_{peak}) between exercise modes (n^2=0.712, p<0.001), a large effect was observed for peak rating of perceived exertion (RPE) between exercise modes (n^2=0.390, p=0.007), and a medium effect was observed for the PACES (Physical Activity Enjoyment Scale) total between exercise modes (n^2=0.255, p=0.052). **Study 3)** The results of study three suggest that SIT is effective at improving aerobic capacity, hemodynamic function, and muscle power. There was a small effect of time on body mass index (BMI; p=0.210, n^2=0.122), a small effect of time on systolic blood pressure (p=0.111, n^2=0.167), a medium effect of time on diastolic blood pressure (p=0.027, n^2=0.260), a large effect of time on mean arterial pressure (p=0.027, n^2=0.260), no effect of time on resting heart rate (p=0.578, n^2=0.045), a medium effect of time on peak heart rate (HR_{peak}; p=0.032, n^2=0.250), no effect of time on postural sway (p=0.258, n^2=0.107), a large effect of time on muscle power measured by the Herbert 6s peak power output (PPO) test (p=0.018, n^2=0.517), a large effect of time on countermovement jump power (p=0.008, n^2=0.332), a large effect of time on countermovement jump height (p=0.004, n^2=0.370), a small effect of time on $\dot{V}O_{2max}$ (p=0.017, n^2=0.137), no effect of time on O_2 pulse (p=0.289, n^2=0.009), a medium effect of time on the anaerobic threshold (AT) as a percentage of $\dot{V}O_{2max}$ (AT % @ $\dot{V}O_{2max}$) (p=0.035, n^2=0.243), and a medium effect of time on power at $\dot{V}O_{2max}$ (p=0.010, n^2=0.292).

Conclusion:

The systematic review meta-analysis observed increased aerobic capacity, muscle power, muscle strength, lean body mass, and decreased fat mass with HIIT in older adults. However, the low number of studies reduces the reliability of findings. Peak power output recovery in older adults

is similar at 3- and 5-days following SIT. SIT performed as different exercise modes (static sprinting, cycle ergometer, box stepping) result in different physiological, psychological, and perceptive responses. Static sprinting SIT performed twice a week over 8 weeks improves aerobic capacity, muscle power, and hemodynamic function in already physically active older adults.

Certificate of Ethical Approval

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16 October 2018

Our Ref: DC/SB

Zerbu Yasar
MSS
Bowerham Road

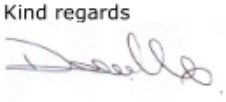
Dear Zerbu

Request for Ethical Clearance – Our Ref: 16/74
Project: SIT in Ageing Populations: Exercise Validation, Adaptation, Enjoyment and Adherence

Thank you for your recent request to update and amendments to your application now placed on file. However, please note that you need to keep the consent form on one side of A4 to ensure that signatures are not detached from what has been agreed/disagreed.

Approval granted through Chair's Action.

Kind regards



Professor Diane Cox
Chair
Research Ethics Panel

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Publication Declaration

I declare that the work in this thesis is entirely my own, except for work that has been published in peer reviewed journals:

Peak Power Output Is Similarly Recovered After Three- and Five-Days' Rest Following Sprint Interval Training in Young and Older Adults

Yasar, Z., Dewhurst, S., & Hayes, L. D. (2019). Peak Power Output Is Similarly Recovered After Three- and Five-Days' Rest Following Sprint Interval Training in Young and Older Adults. *Sports*, *7*(4), 94. https://doi.org/10.3390/sports7040094

Sprint Interval Training (SIT) Reduces Serum Epidermal Growth Factor (EGF), but Not Other Inflammatory Cytokines in Trained Older Men.

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High Intensity Interval Training (HIIT) as a Potential Countermeasure for Sarcopenia: A Scoping Review

Hayes LD, Elliott BT, Yasar Z, Bampouras TB, Sculthorpe NF, Sanal Hayes NEM, Hurst C (2021) High intensity interval training (HIIT) as a potential countermeasure for sarcopenia: A scoping review. *Front Physiol*. In press.

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Abbreviations

1RM One Repetition Maximum

ACSM American College of Sports Medicine

AMP Adenosine Monophosphate

AMPK 5' Adenosine Monophosphate-Activated Protein Kinase

ANOVA Analysis of Variance

AT Anaerobic Threshold

BLa Blood Lactate

BLa_{peak} Peak Blood Lactate

BMI Body Mass Index

BMR Basal Metabolic Rate

CaMKII Calmodulin-Dependent Protein Kinase 2

CI Confidence Interval

CMJ Countermovement Jump

CO_2 Carbon Dioxide

CR-10 Category Ration 10 Scale

DNA Deoxyribonucleic Acid

GH Growth Hormone

GLUT4 Glucose Transporter Type 4

HIIT High Intensity Interval Training

HR Heart Rate

HR_{max} Heart Rate Maximum

I^2 Higgins I^2 Statistic

IGF-1 Insulin Growth Factor 1

IIS Insulin/Insulin-Like Growth Factor 1 Signaling Pathway

LEX Lifetime Exercisers

MICT Moderate Intensity Continuous Training

MPB Muscle Protein Breakdown

MPS Muscle Protein Synthesis

mRNA Messenger Ribonucleic Acid

NAD+ Nicotinamide adenine dinucleotide

O_2 Oxygen

OBLA Onset of Blood Lactate

PACES Physical Activity Enjoyment Scale

PAR-Q Physical Activity Readiness Questionnaire

PGC-1a Peroxisome Proliferator-Activated Receptor Gamma Coactivator 1-Alpha

PPO Peak Power Output

PRISMA Preferred Reporting Items for Systematic Reviews and Meta-Analyses

RE Random Effects

RCT Randomised Controlled Trial

RNA Ribonucleic Acid

ROS Reactive Oxygen Species

RPE Rating of Perceived Exertion

RPE_{peak} Peak Ratings of Perceived Exertion

RST Repeated Sprint Training

SD Standard Deviation

SDM Standard Difference in Means

SED Sedentary

SIRT1 Sirtuin Signalling Pathway

SIT Sprint Interval Training

UCT Uncontrolled Trial

$\dot{V}O_2$ Oxygen Uptake

$\dot{V}O_{2max}$ Maximal Oxygen Uptake

$\dot{V}O_{2peak}$ Peak Oxygen Uptake

WHO World Health Organisation

Chapter 1: Introduction and Literature Review

1.1 Introduction

High intensity interval training (HIIT) is defined by periods of higher exertion, generally corresponding to >85% of maximal oxygen uptake ($\dot{V}O_{2max}$), interspersed with periods of lower intensity recovery (MacInnis and Gibala, 2016). This contrasts with moderate intensity continuous training (MICT), which utilises an intensity of <70% $\dot{V}O_{2max}$ without significant variations in intra-session intensity (Su et al., 2019). HIIT has gained in popularity due to its purported efficiency, with regards to decreased training time and volume, without compromising physiological adaptations when compared against medium intensity continuous training (MICT) (MacInnis and Gibala, 2016). Interestingly, however, HIIT does not have a single uniform format of application, with 11 separate approaches identified by previous research (Laursen and Buchheit, 2013a). This scope for modification makes HIIT versatile in targeting different physiological parameters, yet it simultaneously increases its complexity.

Previous research in healthy, physically active younger populations below 40 years of age has demonstrated the feasibility of HIIT to increase $\dot{V}O_{2max}$ (Milanovic et al., 2015). Likewise, similar benefits have been reported in sedentary and trained older cohorts aged over 60 years for aerobic, muscular, and endocrine measures of health (Grace et al., 2015; Herbert et al., 2017). This is important, as aerobic, muscular, and endocrine physiological potential gradually declines within a decade following physiological maturation in humans, which occurs in the 3rd decade of life (Chahal and Drake, 2007; Fleg, 2012; Janssen et al., 2000). Therefore, HIIT may have a role in slowing against this inevitable physiological decline (Lopez-Otin et al., 2013). However, although HIIT may be more time-efficient, the intensity required of individuals during a HIIT sessions has been postulated to be a major barrier to adoption (Biddle and Batterham, 2015). Additionally, HIIT is not easy to prescribe due to effort requirements which are hard to perceive, for instance,

when HIIT sessions require individuals to perform at 100% of $\dot{V}O_{2max}$ intensity, this does not correspond with 100% of maximal voluntary contraction forces from the individual (MacInnis and Gibala, 2016). These sub-maximal forces are harder to exert precisely, particularly with older adults, due to diminished proprioception, and therefore, requirements for specialised equipment such as power meters, and heart rate monitors are increased (Proske and Gandevia, 2012). This is likely to create a further barrier to effective mass adoption. Previous research has indicated potential hazards with HIIT in older adults, pertaining to both muscle peak power recovery, and a delay in recovery of pre-exercise postural stability, both of which increase the potential for falls and associated injuries (Donath et al. 2014; Herbert et al., 2015b).

Overall, although HIIT is seemingly useful within older populations aged 60 years and above of varying fitness levels, there are barriers to its adoption that may not be shared by sprint interval training (SIT) (Biddle and Batterham, 2015; Donath et al., 2014; Herbert et al., 2015b; Proske and Gandevia, 2012. SIT, unlike HIIT, is often performed at intensities that require maximal effort over a short period of time, generally between 10-30 seconds (Sloth et al., 2013). This likely allows for a greater proprioceptive understanding of effort requirements, which does not necessitate specialised equipment to measure power output (Proske and Gandevia, 2012). Moreover, SIT sessions are generally even shorter than HIIT sessions, with a lower volume of work, demonstrating its time-efficiency (MacInnis and Gibala, 2016). Combined with reports from previous research of SIT demonstrating lower perceived exertion, SIT may present an opportunity to investigate a training mode for older adults that is time-efficient, tolerable, whilst being easier to understand and perform (Vollaard and Metcalfe, 2017a). However, research concerning SIT in older adults is sparse to non-existent. To date, there is only one research article that assesses the effectiveness of maximal effort sprint intervals in adults, conducted by Adamson

et al. (2014) and Adamson et al. (2018), which more closely resembled repeated sprint training (RST) than SIT as described and defined previously by Laursen and Buchheit (2013a). Therefore, further research needs to be conducted concerning the safety, practicability, tolerability, and efficacy SIT in older adults.

1.2 Literature Review

1.2.1 Physical Activity, Health, and Lifespan

As of 2019, the United Nations estimates a doubling in the number of people aged 60 years or above by the year 2050 (United Nations, 2020). According to the World Health Organisation (WHO), this equates to a total of 2 billion people aged >60 years (WHO, 2015). In Europe, it is projected that approximately 30% of the population will be aged >65 years by 2060 (Walker and Maltby, 2012). In developing countries, this can be attributed to decreased childbirth and early life mortality (Bloom, 2011).

At present, the scientific evidence suggests that the maximal human lifespan is limited organically (without specialised modern interventions) to ~115 years (Dong et al., 2016). However, Ben-Haim et al. (2017) postulated that inorganic interventions, such as pharmaceutical intervention, alongside biological and genetic factors may be able to increase this figure by ~30%. There is currently no evidence to suggest that physical activity in any form can increase this maximal organic limit. Furthermore, the remote possibility of increasing maximal human lifespan has initiated a shift in scientific focus, towards what is referred to as the human health span (Olshansky, 2018). Olshansky (2018), describes this as the length of time that an individual remains relatively healthy. Although the review by Rebelo-Marques et al. (2018) suggests

evidence of the anti-ageing effects of exercise, (encompassing aerobic, resistance and flexibility training) it is more likely that various exercise types and modes facilitate optimisation of a healthier ageing process for all individuals, excepting extreme instances of individuals suffering from rare or terminal disease. Moreover, there is strong evidence that increasing the average human lifespan and health span can be achieved with regular physical exercise, both aerobic and anaerobic, attributable mainly to reduced mortality risks (Mora and Valencia, 2018).

1.2.2 Physical Activity and Age

Generally, older adults are comparably less physically active than younger adults (Westerterp, 2000). This is despite evidence that, a combination of aerobic, resistance, flexibility, and balance training are recommended to older adults to maintain physical fitness (Galloza et al., 2017). Aerobic exercise training is defined as exercise that engages large muscle groups in a repetitive cycle for sustained period of 10 minutes or more whereas resistance exercise training is defined as exercise that utilises a resistive force or weight to engage muscles. Present evidence suggests that the most impactful forms of exercise for older individuals pertaining to their physical function are aerobic exercise and resistance exercise training (Garatachea et al., 2015).

Even the fittest older adults, masters athletes, are less physically capable following the 4th decade of life, with accelerating declines in physical capability following the 5th and 6th decades of life (Tanaka and Seals, 2008). Importantly however, masters athletes generally attenuate age-associated losses to physical performance relative to less active peers (Reaburn and Dascombe, 2008). Increased physical fitness in older adults has demonstrably improved neural, cardiovascular, lung, muscle, and metabolic function, alongside improved body composition

measures (Garatachea et al., 2015). Quality of life and general well-being are improved with metabolically intense exercise, such as aerobic training in a wide range of ages, ranging from 24 years to 89 years (Gill et al., 2013). In the study by Gill et al. (2013), the benefits of general exercise on quality of life and well-being were investigated across a diverse range of ages and health statuses. The study encompassed participants from multiple groups with varying fitness levels and demographic characteristics. Young to middle-aged women from a single church (aged 24 to 48) comprised two of the groups. The remaining groups, predominantly women, had distinct profiles: novice women runners in a training program (aged 33 to 55), a dancing group (aged 18 to 55), women with fibromyalgia participating in a specific activity program (aged 54 to 83), and a YMCA senior fitness class (aged 65 to 73). Metabolically intensive exercise, such as football, running, basketball also reduces the overall incidence of cancers as opposed to less metabolically intense exercise, such as walking (Thune and Furgerg, 2001). Corroborating this, all-cause mortality risk is reduced by 20-30% with energy expenditures equivalent to 1000 kcal. wk^{-1} above the basal metabolic rate (BMR), and further reductions are observed at higher energy expenditures (I-Min et al., 1995). A combination of aerobic, resistance, flexibility, and balance training are recommended to older adults over 60 years of age to maintain overall physical fitness and function (Galloza et al., 2017).

Aerobic exercise training is defined as exercise that engages large muscle groups in a repetitive cycle for sustained period of 10 minutes or more, whereas resistance exercise training is defined as exercise that utilises a resistive force or weight to engage muscles. Present evidence suggests that the most impactful forms of exercise for older individuals over 60 years of age pertaining to their physical function are aerobic exercise and resistance exercise training (Garatachea et al., 2015). Emerging evidence supports the effectiveness of high-intensity interval training (HIIT)

protocols in enhancing physiological outcomes in older adults over 60 years of age. Studies on HIIT in older adults indicate improvements in muscle function, with increases in strength and power ranging from 4.5% (Hurst et al., 2019) to 13.7% (Bruseghini et al., 2015). Aerobic capacity, as measured by V̇O2max, exhibited significant enhancements, increasing from 5% (Boukabous et al., 2019) to as high as 15.6% (Molmen et al., 2012). Body fat showed notable reductions, ranging from 1.3% (Søgaard et al., 2017) to 4.4% (Lepretre et al., 2009). Increases in lean mass varied from 1.1% (Hwang et al., 2016) to 4% (Herbert et al., 2016). These findings underscore the potential of HIIT in promoting overall health and well-being in the aging population.

1.2.3 Ageing, Exercise, and Cardiorespiratory Fitness

Cardiorespiratory fitness plays a pivotal role in maintaining overall health and well-being particularly in older adults, where age-associated declines in aerobic capacity led to a greater risk of age-related diseases and decreased quality of life (Fleg et al., 1986; Talbot et al., 2000). Given the importance of maintaining cardiorespiratory fitness in older adults, it is crucial to determine the most effective exercise prescriptions for this population. Improvements in maximal oxygen uptake (V̇O2max) because of different types of exercise training over an 8-week period can be varied. With moderate-intensity continuous training (MICT), one can generally expect an increase of around 3-20%, contingent on the specifics of the training regimen and the initial fitness level of the individual (Murphy et al., 2019). HIIT has been shown to elevate V̇O2max by about 5-15%, although the exact percentage can largely depend on the intensity and duration of the intervals used (Helgerud et al., 2007). As for sprint interval training (SIT), research indicates an increase in V̇O2max of approximately 4-13% in just 2 weeks, suggesting potentially greater gains over an 8-week period (Burgomaster et al., 2008). On the other hand, resistance exercise, primarily being anaerobic, doesn't typically lead to large

increases in V̇O2max, but can still result in a negligible to 5% increase, particularly in individuals with low initial aerobic fitness (Lemmer et al., 2001). As such, targeting cardiorespiratory fitness benefits, the most effective forms of exercise are likely to be one of MICT, HIIT, or SIT. It is important to note that age-related decline in CRF occurs regardless of training status (Pimentel et al., 2003). However, the rate of decline can be mitigated or "flattened" through regular exercise training that is of moderate or high cardiovascular intensity, as such, masters athletes, who typically are aged 35 and above, have been found to experience lesser loss of CRF over an 8-year period compared to their sedentary counterparts (Rogers et al., 1990). This suggests that even small increments in physical activity can result in significant health benefits, a concept that has been supported by several studies (Kaminsky et al., 2013; Kodama et al., 2009).

Furthermore, it's important to highlight that not only consistent exercisers throughout life but also those who start exercising later in life can achieve significant CRF improvements. For example, Knowles et al. (2015) provided evidence that sedentary individuals who adopted an high intensity interval exercise regimen later in life also witnessed considerable benefits in terms of CRF.

Overall, while physical activity is beneficial for all age groups, the type and intensity of exercise, as well as the age when one starts exercising, can influence the extent of improvements in CRF and hence, overall health outcomes.

HIIT has been shown to improve $\dot{V}O_{2max}$ in both young and older adults (Gillen et al., 2013; Milanović et al., 2015). Additionally, HIIT has been associated with improvements in cardiovascular health, insulin sensitivity, and body composition in older individuals (Gibala et al., 2012; Vollaard et al., 2017). The adaptability of HIIT protocols allows for the customisation of

exercise intensity, duration, and frequency to accommodate the specific needs and limitations of older adults (Wisløff et al., 2007). In this context, Buchheit and Laursen (2013a) advise that higher interval duration is generally converse to intensity. For instance, Buchheit and Laursen (2013a) advise shorter and more intense intervals to emphasise the neural stimulus, theoretically improving muscle power improvements. Conversely, longer interval durations with lower intensities emphasise central cardiovascular adaptations, and therefore, increase cardiorespiratory fitness. While research on SIT in older adults is limited compared to HIIT, available evidence suggests that SIT can also improve cardiorespiratory function, metabolic health, and muscular function in this population (Metcalfe et al., 2012; Skelly et al., 2013). For instance, a study by Metcalfe et al. (2012) demonstrated that SIT, consisting of two 20-second maximal sprints on a cycle ergometer, elicited significant improvements in $\dot{V}O_{2max}$ and insulin sensitivity.

In comparison to traditional moderate-intensity continuous training (MICT), HIIT and SIT have been shown to elicit similar or even superior improvements in cardiorespiratory fitness and health markers in young aged below 30 years, and predominantly middle-aged adults aged between 30-60 years, despite the reduced time commitment required (Gibala et al., 2012; Jung et al., 2015). This aspect is particularly relevant for older individuals, who may experience time constraints, physical limitations, or reduced motivation to engage in prolonged exercise sessions. Furthermore, both HIIT and SIT can be adapted to accommodate various fitness levels and orthopaedic concerns, allowing for the inclusion of low-impact exercises, such as swimming or cycling, to reduce the risk of injury (Chodzko-Zajko et al., 2009; Weston et al., 2014).

In summary, HIIT and SIT represent promising exercise modalities for improving cardiorespiratory function and overall health in older adults over 60 years of age. These exercise protocols offer time-efficient alternatives to traditional MICT, with the potential to elicit comparable or superior benefits in terms of $\dot{V}O_{2max}$, cardiovascular health, metabolic function, and muscular performance. By accommodating individual needs and limitations through the customisation of exercise intensity, duration, and frequency, HIIT and SIT can provide older individuals with an effective means of mitigating age-associated declines in cardiorespiratory function and promoting overall health and well-being.

Despite the benefits of HIIT in older adults, some concerns have been raised regarding the safety and tolerability of these high-intensity exercise modalities in this population. However, recent studies have demonstrated that both HIIT and SIT can be safely implemented in older individuals aged 65 years and above, provided that appropriate screening, supervision, and individualisation of exercise protocols are employed (Herrod et al., 2020; Weston et al., 2014). Importantly, older adults should be encouraged to begin with lower-intensity exercise and gradually progress to higher-intensity protocols under the guidance of a qualified exercise professional (Chodzko-Zajko et al., 2009). This progressive approach ensures that older individuals can safely adapt to the increased demands of HIIT and SIT while minimising the risk of injury or adverse events.

1.3 Ageing, Exercise, and Muscle Function

Generally, muscle mass starts to decline after the 3rd decade of life (Janssen et al., 2000; Lexell et al., 1988). Subsequently, 40% of muscle mass is generally lost on entering the 8th decade of life (Saini et al., 2009). There is some evidence to suggest that the age-associated loss of muscle

cross-sectional area may result in reduced muscle strength following the 6th decade of life (Frontera et al., 2000). However, Clark and Manini (2010) suggest that muscle cross-sectional area losses do not necessarily equate to losses in strength. Moreover, muscle strength alone is not an effective measure of muscle function, as muscle power is potentially more relevant to physical function (Byrne et al., 2016). The mechanistic reasons for the cause of losses to muscle function are multifactorial: denervation, diminished satellite cells, impaired muscle protein synthesis, reduced anabolic hormone-receptor affinity, malnutrition, increased basal inflammation, oxidative stress, mitochondrial dysfunction, and sedentarism (Garatachea et al., 2015).

Risk of falling increases with age due to multiple physiological functions deteriorating in the elderly (Deandrea et al., 2010). Importantly, deteriorations in balance and muscle power appear to be the principal factors that contribute to fall risks (Reid and Fielding, 2012). In perspective, one-third of individuals over 65 experience falls once a year, 20% of whom will require medical attention (Chang et al., 2004; Gillespie et al., 2012). Additionally, 20% of elderly who suffer a hip fracture die within 12 months of fracture (Meessen et al., 2014). The high mortality rate is attributable to the loss of mobility and the associated dysregulation of cardiorespiratory and vascular systems, highlighting the risks of sedentary lifestyles. Although the aetiology of falls is likely multifactorial, with muscle weakness, impaired balance and gait, visual impairment, and sex are noted as dominant factors contributing to the likelihood of falling (Ambrose and Hausdorff, 2013). Although balance training has been demonstrably efficacious at preventing falls, the contribution of muscle function is logically evident, considering balance training is targeted training intervention for specific groups of muscles most associated with postural control (Low et al., 2017; Sherrington et al., 2020).

Postural sway, or the continuous shifting of the body's centre of mass while standing, is a crucial measure of balance. It is a marker of body stability, and increased postural sway is linked to an elevated risk of falls in the elderly (Prieto et al., 1996). Methods for quantifying postural sway vary and can be divided into objective and subjective assessment.

Objective measurements include centre of pressure (CoP) excursions, quantified using a force platform, which is a device that measures the ground reaction forces generated by a body standing on it. CoP displacement provides valuable insights into the neuromuscular control of posture and is a primary measurement of postural sway (Mochizuki et al., 2006). Clinically, force platform measures are considered gold standards for assessing balance function and fall risk. Yet, the usage in routine clinical settings is limited due to the high cost, complex setup, and requirement of trained personnel for interpretation.

Inertial measurement units (IMUs), often used in wearable technology, offer a more portable and user-friendly option for postural sway measurement. IMUs measure accelerations and rotations, providing a comprehensive evaluation of postural control, including sway velocity, sway path, and maximum displacement (Mancini et al., 2012). However, interpretation of IMU data is complex and requires specific expertise, limiting its widespread use.

Subjective measurements involve the use of balance scales, such as the Berg Balance Scale (BBS) and the Tinetti Balance Assessment Tool, which are scored by a clinician based on a series of tasks related to balance and gait. While these scales are easier to implement in a clinical setting,

they have some limitations, including potential for bias and a ceiling effect in individuals with mild balance impairments (Steffen et al., 2002).

Normative values for postural sway can vary significantly based on age, sex, and health status. In healthy adults, the average sway path during quiet stance is typically between 100 and 200 mm/min (Hufschmidt et al., 1980). However, these values can increase substantially with age, with individuals aged over 60 showing approximately 20% greater sway compared to younger individuals (Era et al., 1996). While there's no universally agreed threshold for excessive postural sway, some research suggests that sway paths greater than 300 mm/min may be associated with increased risk of falls (Hufschmidt et al., 1980).

In conclusion, the measurement of postural sway offers valuable insight into balance control and fall risk in the elderly. Various methods of assessment offer differing advantages and drawbacks, and a comprehensive evaluation should incorporate multiple assessment modalities. Further research is necessary to establish standardised thresholds for fall risk, facilitating the implementation of targeted interventions to improve balance and reduce the risk of falls in the elderly population.

The current consensus on prescribing resistance exercise training to older individuals suggests a frequency of twice a week, with moderate to high perceptual intensity, using progressive increases to work against resistance for the major muscle groups (Chodzko-Zajko et al., 2009). Chodzko-Zajko et al. (2009) further defines that each session could utilise approximately 8-10 compound resistance exercises, and can be achieved using weights, bands, and body weight-

bearing exercises. For instance, commonly used compound resistance exercises are bench pressing, deadlifting, squatting. At present, it is suggested that resistance exercise training may be a primary defence against age-associated losses to physical function associated with sarcopenia, dynapenia, and osteoporosis, all of which are leading causes of frailty, disability, and increased mortality (McLeod et al., 2019). However, at present, less than 20% of older adults aged 55 years and above, and less than 10% of those aged 75 years and above compliant with these recommendations (Strain et al., 2016). Therefore, further research is required on training modes that increase muscle function in older adults.

A meta-analysis conducted by Søgaard et al. (2019) found that HIIT and SIT interventions led to significant improvements in muscle strength and power in older adults and therefore, incorporating HIIT and SIT into exercise programs for older adults may enhance muscle function, strength, and power while also improving overall health and functional performance. This could be particularly important given the relatively low uptake of resistance training in older adults.

1.4 High Intensity Interval Training (HIIT)

HIIT is a form exercise utilising high-intensity intervals approximating equal to or above 80% HR_{max} or $V\dot{O}_{2max}$, interspersed with recovery phases, whereas SIT is a sub-category of HIIT generally utilising 'all-out' maximal efforts interspersed with recovery periods (MacInnis and Gibala, 2016). Additionally, SIT is generally shorter in duration with a lower volume of work (MacInnis and Gibala, 2016). Moreover, SIT often utilises absolute maximal bursts of efforts, which removes the requirement for complex intensity calculations, increasing ease of application (Buchheit and Laursen, 2013a).

The rationale for the increased scientific interest in HIIT is due to the present evidence that physiological adaptations to HIIT and SIT are comparable or superior when compared with more traditional methods of aerobic training, such as, moderate intensity continuous training (MICT) (Burgomaster et al., 2005; Burgomaster et al., 2008; Gist et al., 2014; Milanovic et al., 2014 Weston et al., 2014), despite falling short of the 150 min·wk^{-1} recommended for cardiometabolic health (Riebe et al., 2015). Buchheit and Laursen (2013a) propose that HIIT can target a range of physiological mechanisms to instigate adaptations, with emphasis on aerobic, anaerobic, and neuromuscular physiology. Thus, HIIT may be a more versatile form of training when compared with aerobic exercise training or resistance exercise training, with aerobic exercise training primarily targeting aerobic, and resistance exercise training primarily targeting anaerobic and neuromuscular adaptations amongst all age groups, irrespective of training status (Chodzko-Zajko et al., 2009). The extent to which HIIT can be adjusted is dependent on nine factors: mode of exercise, work and rest intensity and duration, number of series, series durations, the time between series, and the between series recovery intensity (Buchheit and Laursen, 2013a). However, Buchheit and Laursen, 2013a, do caution that high volumes and/or frequencies of HIIT can yield detrimental effects on adaptation, and training should be adjusted to allow for sufficient recovery between sessions.

In terms of cardiorespiratory fitness, the greatest increase in $\dot{V}O_{2max}$ was observed by Molmen et al., 2012 (15.6%) in older adults around 72 years old, utilising treadmill running with 4 x 4-minute intervals at ~87% V̇O2max. Lepretre et al., 2009 reported increases in V̇O2max of 14.7% and 14.5% in older men and women (averaging 65 and 66 years, respectively), with a cycling exercise protocol involving 6 x 1-minute intervals at ventilatory threshold two. Concerning

muscle power, Herbert et al., 2017 discovered an 8.3% increase in male master athletes (average age: 61 years), following a cycling exercise regimen of 6 x 30-second intervals at 40% peak power output. For muscle strength, the most significant increase (13%) was seen in older women averaging 66 years old (Boukabous et al., 2019) after a treadmill exercise protocol of 6 x 1-min intervals at 90% HR reserve. Bruseghini et al., 2015 and 2019 reported 13.7% and 12.9% increases in muscle strength in healthy elderly subjects and healthy older males (both average age 68 years), respectively, utilising aerobic and cycling interval training exercises. Regarding lean mass, Herbert et al., 2016 noted the highest increase (4.0%) in master athletes around 60 years old, using a HIIT programme involving 6 x 30-second sprints at 40% PPO. In terms of fat mass, Lepretre et al., 2009 documented the greatest reduction (4.4% and 4.3%) in older men and women (averaging 65 and 66 years, respectively), with a cycling exercise protocol. A considerable increase in fat-free mass (4.0%) was observed in master athletes by Herbert et al., 2016, utilising the same HIIT protocol as for lean mass. Fitness levels of participants varied across studies, with some focusing on sedentary older adults, such as Hwang et al., 2016, Kim et al., 2017, and Knowles et al., 2015, and others, like Herbert et al., 2017 and 2016, focusing on master athletes or those already exercising. These studies underscore HIIT protocol's adaptability to various ages and fitness levels, enabling tailored exercise interventions that yield significant improvements in physical fitness.

1.4.2 Key Differences Between HIIT and Aerobic Exercise Training

Improved cardiovascular fitness following habitual aerobic exercise and/or training that stresses the cardiovascular system are well established, with increased cardiac output and decreased vascular resistance noted as key adaptations in increased the cardiovascular capacity in humans (Lindholm et al., 2016). There is some evidence that HIIT successfully mimics several

physiological adaptations that are observed in aerobic exercise training (Milanovic et al., 2015). Aerobic exercise training is a potent stimulator of enhanced skeletal muscle substrate metabolism (Holloszy and Coyle, 1984). Even with limited training phases of 5-7 days, glycogen availability and sparing are enhanced, culminating in enhanced endurance performance (Green et al., 1992; Chesley et al., 1996). Aerobic training adaptations are often attributed to enhanced mitochondrial function (Lundby and Jacobs, 2016), cardiac remodelling, vascular function, and capillarisation (Ellison et al., 2012; Seals et al., 2009). Interestingly, similar findings are present in HIIT studies (Little et al., 2011; Mahjoub et al., 2019), although, Laughlin and Roseguini et al, (2008) observed different effects on blood-flow capacity attributed to the altered artery and capillary function between aerobic exercise training and HIIT. The authors reported that blood flow within red gastrocnemius muscle - which is higher in type 1 slow-twitch fibres - was better enhanced by aerobic exercise training, whilst the HIIT protocol was observed to enhance blood flow in white gastrocnemius muscle - which has a higher proportion of type 2 fibres compared with type 1 fibres. These results suggest that HIIT may induce peripheral fatigue more than aerobic exercise training, whilst aerobic exercise training may achieve central cardiovascular fatigue. Moreover, the predominant method of activating the signalling of peroxisome proliferator-activated receptor-gamma coactivator 1-alpha (PGC-1a), a protein 'master regulator' signal required in the process of mitochondrial biogenesis, differs between aerobic exercise training and HIIT (Wu et al.,1999). In aerobic exercise training, calcium-calmodulin dependent kinase 2 (CaMKII), is the dominant contributor to PGC-1a activation, due to the higher volume of work required to activate the CaMKII pathway (Rose et al., 2007). Alternatively, HIIT appears to be a potent stimulator of the adenosine monophosphate-activated protein kinase pathway (AMPK), which is activated by higher intensity bouts of exercise (Gibala et al., 2012).

1.4.3 Afferent Responses to HIIT

HIIT research has comprised more psychometric analysis in recent years (Biddle and Batterham, 2015). There is some literature suggesting HIIT is not suitable for breaking barriers to exercise participation, due to it being intolerable (Hardcastle et al., 2014). However, Hardcastle et al. (2014), examined Wingate sprints of 30 seconds, interspersed with ~2 minutes of rest. This suggestion is corroborated by the postulation from Gibala et al. (2012) that Wingate style HIIT may be overly demanding, intolerable, and a potential health hazard to ill-prepared individuals. It is important to note that HIIT does not require this level of difficulty. For instance, Vollaard and Metcalfe (2017b), demonstrated lesser intervals lengths of 15 to 20 seconds are equally effective at increasing physical fitness with young, healthy, and previously untrained participants. This is encouraging as Ekkekakis (2011) theorised that higher exercise intensities described as high levels of cardiovascular or respiratory stress (measured by perceived exertion) were abrasive to an individual's enjoyment and willingness to repeat an exercise. Importantly, enjoyment of exercise is a key predictor of future adherence (Ekkekakis., 2009; Emmons and Deiner., 1986; Williams et al., 2008; Lee et al., 2016). On the contrary, Oliveira et al. (2018) provided meta-analytical evidence that HIIT was not just equally enjoyable as steady-state aerobic training, but potentially more enjoyable. Therefore, the evidence regarding exercise intensity and enjoyment is far from reaching consensus and provides justification for further research to be conducted.

1.5 Exercise and Ageing Biology

Ageing is not simply a consequence of time, but involves a loss of physiological integrity, influenced by factors like chronic inflammation or "inflammageing" and excess reactive oxygen species, which damage cellular structures and lead to diseases (Lopez-Otin et al., 2013; Zuo et al.,

2019). Nine biological processes including genomic instability, telomere attrition, epigenetic changes, and others, control ageing and correlate with functional declines in various capabilities (Lopez-Otin et al., 2013; Garatachea et al., 2015). However, physical activity and exercise can positively impact these processes, promoting health and potentially extending lifespan (Rebelo-Marques et al., 2018).

Deregulated nutrient sensing is a major issue during the ageing process, as it can lead to diminished responses to exercise, impaired metabolic regulation, and reduced overall health. In older adults, it is important to understand the complex interaction between growth hormone, Insulin/Insulin-like growth factor-1 (IGF-1) signaling, protein kinase B (PKB)/Akt, mammalian target of rapamycin (mTOR), phosphatase and tensin homolog (PTEN), Forkhead box protein O1 (FOXO1), AMP-activated protein kinase (AMPK), sirtuin signalling pathway (SIRT1), and peroxisome proliferator-activated receptor-gamma coactivator-1 alpha (PGC-1α).in relation to dietary restriction and inflammageing (Efeyan et al., 2015).

Growth hormone (GH) is an essential component of the aging process and deregulated nutrient sensing. GH and insulin-like growth factor 1 (IGF-1) have been shown to regulate the IIS pathway, a cell signaling pathway which can influence cellular growth and metabolism (Hakuno and Takahashi, 2018). With ageing, there is a reduction in IIS, which could be a compensatory mechanism to reduce cell growth and metabolism that are compromised during ageing (Schumacher et al., 2008; Garinis et al., 2008). This reduction in IIS has been linked to a decline in GH and IGF-1 levels, which are essential for maintaining cellular growth, metabolism, and overall health (Bartke et al., 2003; Wrigley et al., 2017).

The Akt/PKB pathway is another crucial component of nutrient sensing, as it is involved in the regulation of cell growth, survival, and metabolism. Akt/PKB is activated by insulin and IGF-1, resulting in the activation of mTOR, a potent regulator of anabolic metabolism (Manning and Toker, 2017). The activation of mTOR is sensitive to amino acid concentrations and plays a role in the adaptive process of muscle development in older adults (Houtkooper et al., 2010). However, with ageing, the mTOR signaling pathway can become deregulated, leading to decreased anabolic responses and increased catabolic processes (Laplante and Sabatini, 2012).

PTEN is a crucial negative regulator of the Akt/PKB pathway and is involved in the regulation of cellular growth and survival (Knobbe et al., 2008). The deregulation of PTEN during aging could contribute to the impaired regulation of the Akt/PKB pathway and the subsequent decline in muscle mass and function (Greer and Brunet, 2005).

The FOXO1 transcription factor is another essential component of nutrient sensing, as it plays a role in regulating glucose metabolism, energy homeostasis, and oxidative stress response. The activation of FOXO1 can be inhibited by the IIS pathway, which may contribute to the impaired glucose metabolism observed in aging (Salih and Brunet, 2008).

AMPK and SIRT1 are both sensitive to cellular energy status and play a critical role in nutrient sensing. AMPK is activated in response to low cellular energy levels, while SIRT1 is activated by high NAD+ levels (Houtkooper et al., 2010). The deregulation of AMPK and SIRT1 signaling

pathways during ageing can impair the regulation of cellular energy metabolism and contribute to the development of age-related metabolic disorders (Canto and Auwerx, 2011).

PGC-1α is a transcriptional coactivator that plays a central role in mitochondrial biogenesis and energy metabolism. The activation of PGC-1α is regulated by AMPK and SIRT1, and its function is compromised during aging, leading to a decline in mitochondrial function and oxidative capacity (Perez et al., 2020).

Dietary restriction has been shown to extend the lifespan of several species, and this is thought to be, at least in part, due to improvements in nutrient sensing and reduced inflammation (Fontana and Partridge, 2015). Dietary restriction can increase the activity of AMPK, SIRT1, and PGC-1α, while also downregulating the IIS and mTOR signaling pathways (Kenyon, 2010). This can result in improved glucose metabolism, increased mitochondrial biogenesis, and reduced oxidative stress, which could potentially contribute to the extension of lifespan and improved overall health during aging (Fontana et al., 2010).

Inflammageing refers to the chronic low-grade inflammation that occurs during ageing, which can contribute to the development of age-related diseases (Franceschi et al., 2000). Deregulated nutrient sensing pathways, such as IIS, mTOR, and AMPK, can exacerbate inflammageing by promoting the production of pro-inflammatory cytokines and reactive oxygen species (ROS) (López-Otín et al., 2013). However, with ageing, this equilibrium can be disturbed, leading to a state of "oxidative stress," characterized by an excess of reactive oxygen species (ROS). This excess ROS can damage cellular components, such as proteins, lipids, and DNA

(Deoxyribonucleic Acid), which has been implicated in the aging process and various age-related diseases, such as neurodegenerative diseases, cardiovascular diseases, and cancer (Harman, 1956; Liguori et al., 2018).

ROS is produced as a by-product of cellular metabolism, especially during mitochondrial oxidative phosphorylation. However, ROS can also be intentionally produced by certain enzymes to serve as signalling molecules. In this context, a moderate increase in ROS can promote cellular adaptation to stress, a process known as hormesis (Ristow and Schmeisser, 2014). For instance, physical exercise increases the production of ROS, which can lead to adaptations in skeletal muscle, enhancing antioxidant defences, and improving insulin sensitivity (Gomez-Cabrera et al., 2008).

Furthermore, emerging evidence suggests a complex interplay between ROS, nutrient-sensing pathways, and the ageing process. For example, mTOR signalling, which is implicated in nutrient sensing and ageing, can influence ROS production (Zoncu et al., 2011). Subsequently, ROS can regulate mTOR signalling, suggesting a reciprocal relationship (Schieber and Chandel, 2014).

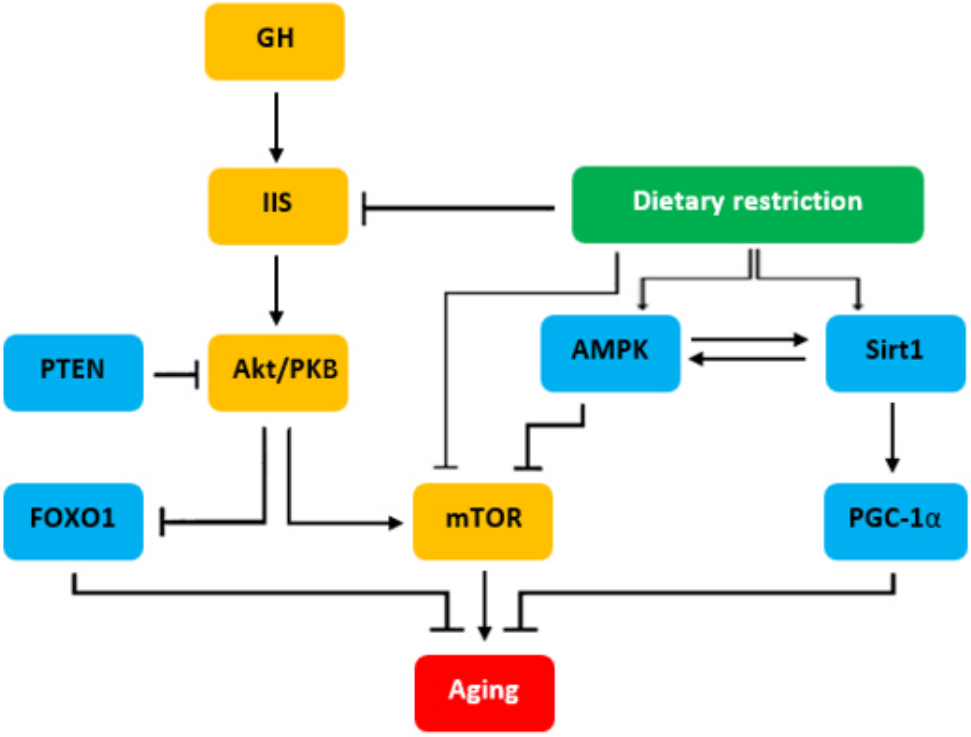
Growth hormone (GH), produced by the anterior pituitary gland facilitates insulin growth factor 1 (IGF-1) secretion following resistance exercise training, with the potential to act in an autocrine or paracrine pattern (Hakuno and Takahashi, 2018). Interestingly, insulin and IGF-1, both sensitive to glucose, elicit the same signalling pathways, as such, they are referred to together as the insulin/insulin-like growth factor 1 signaling pathway (IIS), and attenuating the declining function of IIS has the effect of increasing the lifespan of some species (Bartke et al., 2003;

Wrigley et al., 2017). Interestingly however, IIS is reduced in humans following the 3rd decade of life (Lopez-Otin et al., 2013). Garinis et al. (2008) suggest that the reduction of IIS may be a compensatory process to reduce cell growth and metabolism, both of which are increasingly compromised by the ageing process (Figure 1.5.1) (Lopez-Otin et al., 2013). Other nutrient-sensing systems that are compromised with ageing are mechanistic target of rapamycin (mTOR) signalling, sensitive to amino acid concentrations, and a potent initiator of anabolic metabolism; adenosine monophosphate-activated protein kinase (AMPK) and sirtuin siganlling pathway (SIRT), which is sensitive to low cellular energy due to high adenosine monophosphate (AMP) or high nicotinamide adenine dinucleotide (NAD+) levels respectively (Houtkooper et al., 2010).

IIS, mTOR, AMPK, and SIRT signalling are sensitive to exercise, the type of exercise, and the availability of nutrients (Hawley et al., 2014). Increased physical activity has been observed to increase the GLUT4 transporter of glucose, thereby improving the sensitivity of the IIS pathway (Mann et al., 2014).

Both resistance and endurance exercise can influence nutrient sensing pathways, including the activation of AMPK and SIRT1 and the modulation of IIS and mTOR signaling (Hawley et al., 2014). Expanding on this theory by Hawley et al., (2014), it is likely that HIIT and SIT activates health promoting pathways similarly, as previous research has observed muscular hypertrophy (Gibala et al., 2012; Gillen et al., 2016) and mitochondrial biogenesis (MacInnis et al., 2017) following intense interval exercise interventions. Importantly, muscle hypertrophy is conducive and generally a pre-requisite to improving overall muscle function and insulin sensitivity (Frontera et al., 1988; Hawley et al., 2004). Similarly, improved mitochondrial biogenesis is a

pre-requisite for increase cardiorespiratory function (Holloszy et al., 2008; Menshikova et al., 2006).



KEY:

GH = Growth Hormone

IIS = Insulin/Insulin-like Growth Factor Signaling

Akt/PKB = Protein Kinase B

PTEN = Phosphatase and Tensin Homolog

FOXO1 = Forkhead Box Protein O1

AMPK = AMP-Activated Protein Kinase

SIRT1 = Sirtuin 1

PGC-1α = Peroxisome Proliferator-Activated Receptor Gamma Coactivator 1-Alpha

Figure 1.5.1 Deregulated nutrient sensing and its relation to anti and pro ageing factors. Figure demonstrates how deregulated nutrient sensing can influence ageing. Blue items on the figure have anti-ageing effects, whilst orange items have pro-ageing effects.

1.6 Methodological Considerations

Despite the evidence of enhanced health and performance within older adults (Gallo-Villegas et al., 2018; Grace et al., 2017; Hayes et al., 2017; Herbert et al., 2017; Knowles et al., 2015; Sculthorpe et al., 2015; Sculthorpe et al., 2017; Sogaard et al., 2018; Storen et al., 2016), sub-maximal HIIT prescription may be difficult to implement within an older demographic. One barrier may be the intensity adjustment outside of the laboratory environment, where availability of specialised equipment is reduced, or the potentially longer durations required. Therefore, an easier to prescribe and follow protocol, for which SIT is a suitable candidate, is a prudent research area to increase physical fitness in older adults. Moreover, SIT type training is more geared towards neuromuscular development, as such, SIT is better suited to development of power (Buchheit and Laursen, 2013a). This is important, as muscular power is likely the most important factor in older adults maintaining independence (Byrne et al., 2016). Maximal intensity exercise has previously been suggested to potentiate risks to cardiac, muscular, joint, and orthopaedic health for older individuals not accustomed to physical exercise, or individuals with ill-health (Vina et al., 2016). As such, prior to targeting the already frail or oldest old, it would be prudent to conduct research of SIT in older adults within a population familiar with physical exercise and the associated exertion.

1.7 Justification of Research

HIIT, and particularly SIT, has not been extensively researched in older populations. Promisingly, HIIT in young to middle-aged populations increases physical fitness, reduces risk of chronic diseases, and increases quality of life (Gibala et al. 2012; Weston et al. 2014a; Jelleyman et al. 2015; Ramos et al. 2015). Similarly, emerging data concerning HIIT in healthy older adults

suggests viability for increasing physical fitness, (Boukabous et al., 2019; Bruseghini et al., 2015; Bruseghini et al., 2019; Grace et al., 2018; Herbert et al., 2016; Herbert et al., 2017; Hurst et al., 2019; Hwang et al., 2016; Kim et al., 2017; Knowles et al., 2015; Lepretre et al., 2009; Molmen et al., 2012; Sculthorpe et al., 2017; Sogaard et al., 2017; Sogaard et al., 2019; Storen et al., 2017; Wyckelsma et al., 2017), as discussed earlier in the thesis (section 1.4). Although, a more concerted systematic approach is yet to be published in consideration of this literature.

The divergent effects of HIIT in older vs younger populations are not extensively studied. However, some recent work has highlighted that peak power output (PPO) recovery in is 2 days longer than the 3 days required for young healthy males following HIIT (Herbert et al., 2015b). This is important, as any decreases to muscle power may increase health and safety risks in older populations (Byrne et al., 2016). However, no such investigation has investigated recovery from SIT. This necessitates further investigation to establish HIIT and SIT prescription guidelines within this demographic.

Adoption of physical activity guidelines is far from widespread practice is not compliant with recommendations among the public (World Health Organization, 2015). Commonly cited barriers to regular exercise participation are lack of interest, motorised transport access, acute fatigue, joint pain, dislike of isolated evening journeys, perceived lack of fitness, energy, group belonging, alongside doubts of the benefits of exercise and socialising (Crombie et al., 2004), lack of financial resources (Reichert et al., 2007) and enjoyment (Hagberg et al., 2009). Crombie et al. (2004) suggest that physical activity needs to be encouraged by attenuating barriers, if possible. Therefore, before any form of physical activity or exercise can be effectively assessed

for its physiological efficacy, it is imperative to assess if the target demographic can access and want to perform it.

Pertaining to HIIT, the topic of time efficiency and equipment reliance are self-evident, as exercise protocols generally have clear time and equipment requirements (Vollaard and Metcalfe, 2017a), with a net time efficiency against steady state aerobic training being observed in several protocols, including SIT, with varying equipment requirements (Gist et al., 2014; Milanovic et al., 2015; Sloth et al., 2013). Conversely, increasing the complexity, Biddle and Batterham (2015) suggest afferent responses and general applicability of HIIT are likely dependent on multiple factors such as the exercise format and participant fitness. This considered; it is possible that appropriately designed HIIT may be suitable in reducing barriers to exercise. Thus, investigating methods of HIIT that are easy to perform, accessible, practically applicable (widely accessible, easy to prescribe, and time efficient), and enjoyable, whilst maintaining the efficacy for health-generating adaptations seems pragmatic.

Research concerning HIIT and risk of falling and/or balance is unclear (Donath et al., 2014; Sculthorpe et al., 2017), possible as stationary cycling is the most used ergometer, which is unlikely to promote balance adaptations (Ageberg et al., 2003). Given risk of falling is a primary concern for older adults, scope exists for investigating exercise modes that may promote balance improvements. Furthermore, exercise which simultaneously targets muscle function and aerobic adaptations would be of considerable interest, if said exercise did not require specialist equipment (i.e., removed some barriers to exercise-adoption). Taken together, an easy to administer mode of

SIT which targets enhanced physical functioning is of interest. As such, this thesis resulted in the subsequent four aims.

1.8 Aims and Hypotheses of the Thesis

The aims of this thesis were:

1. To consider the current evidence of HIIT interventions in physically active healthy older adults over 60 years of age on fitness variables (aerobic fitness, muscle power, muscle strength, lean body mass, body fat), using a systematic review and meta-analysis.

2. To investigate the duration of power output recovery following SIT in physically active younger below 30 years of age and older adults over 60 years of age at 3 and 5 days of rest.

3. To investigate the acute physiological ($\dot{V}O_2$, blood lactate, heart rate), and afferent (enjoyment, perceived exertion) responses to three SIT protocols (cycling, sprinting, and box stepping) in physically active older adults over 60 years of age.

4. To investigate the effects of SIT in physically active older adults over 60 years of age over 8-weeks on aerobic fitness (e.g., $\dot{V}O_{2max}$), muscular fitness (e.g., peak power output), balance (e.g., postural sway), and cardiometabolic risk factors (e.g., resting heart rate, blood pressure).

1.7 Hypotheses

Chapter 2: Meta-Analysis: Effects of HIIT on older adults

P: Older adults aged 60 years and over I: HIIT interventions C: No exercise intervention or lower intensity exercise intervention

Outcomes and Hypotheses:

1. O1: Improved muscle power
    - H1: HIIT interventions will result in a statistically significant improvement in muscle power when meta-analysed.
    - H01: HIIT interventions will not result in a statistically significant improvement in muscle power when meta-analysed.
2. O2: Improved muscle strength
    - H2: HIIT interventions will result in a statistically significant improvement in muscle strength when meta-analysed.
    - H02: HIIT interventions will not result in a statistically significant improvement in muscle strength when meta-analysed.
3. O3: Increased lean mass
    - H3: HIIT interventions will result in a statistically significant increase in lean mass when meta-analysed.
    - H03: HIIT interventions will not result in a statistically significant increase in lean mass when meta-analysed.
4. O4: Decreased body fat

- H4: HIIT interventions will result in a statistically significant decrease in body fat when meta-analysed.
- H04: HIIT interventions will not result in a statistically significant decrease in body fat when meta-analysed.

5. O5: Improved aerobic capacity

- H5: HIIT interventions will result in a statistically significant improvement in aerobic capacity when meta-analysed.
- H05: HIIT interventions will not result in a statistically significant improvement in aerobic capacity when meta-analysed.

Chapter 3: Recovery of peak power output in older and younger adults following SIT

P1: Older adults over 60 years of age P2: Younger adults aged 30 years or under I: SIT (Sprint Interval Training) C: Comparison of peak power output recovery between older and younger adults O: Recovery of peak power output at three and five days after SIT

Outcomes and Hypotheses:

1. O6: Different recovery of peak power output between older and younger adults

- H6: Peak power output will not be recovered equivalently between older adults aged 60 years and over (P1) and younger adults aged 30 years or under (P2) following SIT (I) at three and five days of recovery (O).
- H06: Peak power output recovery will be equivalent recovered between older adults aged 60 years and over (P1) and younger adults aged 30 years or under (P2) following SIT (I) at three and five days of recovery (O).

Chapter 4: Acute responses to different modes of SIT in physically active older adults

P: Physically active older adults over 60 years of age I1: SIT (Sprint Interval Training) - Cycling I2: SIT (Sprint Interval Training) - Sprinting I3: SIT (Sprint Interval Training) - Box stepping C: Comparison of acute responses to different modes of SIT

Outcomes and Hypotheses:

1. O7: Acute $\dot{V}O_{2max}$ response
    - H7: The acute $\dot{V}O_{2max}$ response to SIT performed in three different modes of exercise (I1, I2, I3) will be different.
    - H07: The acute $\dot{V}O_{2max}$ response to SIT performed in three different modes of exercise (I1, I2, I3) will not be different.
2. O8: Acute HR_{peak} response
    - H8: The acute HR_{peak} response to SIT performed in three different modes of exercise (I1, I2, I3) will be different.
    - H08: The acute HR_{peak} response to SIT performed in three different modes of exercise (I1, I2, I3) will not be different.
3. O9: Acute BLa_{peak} response
    - H9: The acute BLa_{peak} response to SIT performed in three different modes of exercise (I1, I2, I3) will be different.
    - H09: The acute BLa_{peak} response to SIT performed in three different modes of exercise (I1, I2, I3) will not be different.
4. O10: Perceived exertion
    - H10: The perceived exertion to SIT performed in three different modes of exercise (I1, I2, I3) will be different.
    - H010: The perceived exertion to SIT performed in three different modes of exercise (I1, I2, I3) will not be different.

5. O11: Afferent enjoyment response

- H11: The afferent enjoyment response to SIT performed in three different modes of exercise (I1, I2, I3) will be different.
- H011: The afferent enjoyment response to SIT performed in three different modes of exercise (I1, I2, I3) will not be different.

Chapter 5: Effects of 8-week SIT program on physically active older adults

P: Physically active older adults I: 8-week SIT (Sprint Interval Training) program C: Control phase (no SIT intervention)

Outcomes and Hypotheses:

1. O12: $\dot{V}O_{2max}$

- H12: Following 8-weeks of SIT training (I), $\dot{V}O_{2max}$ will increase in physically active older adults over 60 years of age (P) compared with a control phase (C).
- H012: Following 8-weeks of SIT training (I), $\dot{V}O_{2max}$ will not increase in physically active older adults over 60 years of age (P) compared with a control phase (C).

2. O13: Resting heart rate

- H13: Following 8-weeks of SIT training in physically active older adults over 60 years of age (I), resting heart rate will decrease compared with a control phase (C).
- H013: Following 8-weeks of SIT training in physically active older adults over 60 years of age (I), resting heart rate will not decrease compared with a control phase (C).

3. O14: Blood pressure
    - H14: Following 8-weeks of SIT training in physically active older adults over 60 years of age (I), blood pressure will decrease compared with a control phase (C).
    - H014: Following 8-weeks of SIT training in physically active older adults over 60 years of age (I), blood pressure will not decrease compared with a control phase (C).
4. O15: Peak power output
    - H15: Following 8-weeks of SIT training in physically active older adults over 60 years of age (I), peak power output will increase compared with a control phase (C).
    - H015: Following 8-weeks of SIT training in physically active older adults over 60 years of age (I), peak power output will not increase compared with a control phase (C).
5. O16: Balance
    - H16: Following 8-weeks of SIT training in physically active older adults over 60 years of age (I), balance will improve compared with a control phase (C).
    - H016: Following 8-weeks of SIT training in physically active older adults over 60 years of age balance will not improve (I),
    -

Chapter 2: Systematic Review and Meta-Analysis: The Chronic Effects of High-Intensity Interval Training in Older Adults

2.1 Introduction

2.1.1 Rationale

As of 2019, the United Nations estimates a doubling in the number of people aged 60 years or above by the year 2050 (United Nations, 2020). Furthermore, a UK Biobank analysis of approximately half a million participants aged between 37 to 73 years observed that, 3% of adults were frail, and 38% were pre-frail (Hanlon et al., 2018). Importantly, regular physical activity is a potentially cheap, relatively safe, and well researched method of improving physiological functioning, by improving aerobic capacity, muscle power, muscle strength, lean body mass (LBM), whilst having a protective effect against excess body fat (Chodzko-Zajko et al., 2009; Kramer, 2020).

Aerobic capacity as a measure of cardiorespiratory fitness is strongly linked both epidemiologically and mechanistically to prevalence and mortality of cardiovascular disease, a leading cause of death in developed nations (Ozemek et al., 2018). Age associated losses of LBM, muscle strength, and muscle power hold pivotal roles in development of muscle pathologies, such as sarcopenia and dynapenia (Tessier et al., 2019). With the loss of muscle power being associated with decreased physical function, and increased dependence (Byrne et al., 2016). It is proposed that excessive body fat increases pro-inflammatory adipokines and cytokines, and when coupled with reduced anti-inflammatory myokines released in response to muscular contractions, a pro-inflammatory state is proliferated (Lemos Muller et al., 2019). Therefore, indicating the requirement to minimise excess body fat, and optimise LBM, which is inclusive of skeletal muscle.

Not all physical activity has equivalent effects on physiological function, with a generalised contrast between aerobically targeted training vs anaerobically targeted training (Hawley et al., 2014). Aerobic training typically consists of longer durations of above 30-minutes of moderate intensity continuous training (MICT). MICT typically consists of maintaining a steady state of exercise at an intensity between 60-70% of heart rate maximum (HR_{max}). MICT is a popular and effective method of increasing aerobic capacity, cardiorespiratory function, and reducing body fat (Garber et al., 2011). Anaerobic training typically consists of resistance training, with a wide range of single or multi-joint exercises that are performed in sets of repetitions (reps), with the intensity typically determined utilising a percentage of one-repetition maximum (1RM), with intensities ranging from 40% - 85% of 1RM demonstrating efficacy in increasing muscle strength, power, and size (Maren et al., 2019).

MICT and resistance training are well researched, promoted, and demonstrably efficacious. It is evident, however, that a significant proportion of individuals do not partake in these activities, and therefore, are not able to assume the evidenced benefits (Strain et al., 2016). This has emphasised barriers to physical activity, with Crombie et al. (2004), suggesting one of the aims of physical activity should be to reduce barriers. Although it is not possible to establish a single or several training methods that will be universally adopted, it is incumbent on the field of exercise science to investigate various methods of training, with an emphasis on safety, accessibility, and efficacy. Interestingly, Crombie et al (2004) emphasises time spent partaking in physical activity as a desirable outcome. Although this is certainly not an undesirable outcome, training methods should also aim to become more time efficient in propagating improved physiological outcomes. One such training method, high-intensity interval training (HIIT), utilises phases of high intensity efforts, above 80% HR_{max}, alongside, lower intensity recovery phases (MacInnis and Gibala., 2016). This high intensity prescription contrasts the more constant format of MICT. Derived from

HIIT, sprint interval training (SIT), generally utilises 2-6 ‘all-out’ bouts of effort for a short period of time, for approximately 15-30 s, interspersed with recovery periods.

It has been proposed that the increase in exercise intensity performed during HIIT and SIT creates an acute ‘metabolic insult’ which initiates cellular signaling processes which upregulate mitochondrial biogenesis (Fiorenza et al., 2018). Moreover, the increased intensity of muscular contractions and neural demand may provide a basis for increased neuromuscular function, increasing muscle power adaptations (Garcia-Pinillos et al., 2017). As such, HIIT may be a pragmatic 'hybrid' training method, targeting both anaerobic and aerobic adaptative signaling pathways, and should be investigated further. Corroborating this, several meta-analyses have demonstrated that HIIT in young to middle aged adults increases cardiovascular fitness to a similar or superior magnitude when compared with MICT (Batacan et al., 2016; Milanovic et al., 2015; Ramos et al., 2015; Keating et al., 2017).

Although previous meta-analyses have investigated HIIT in older adults, a significant proportion of the studies analysed were not HIIT or SIT as defined by previous literature (Weston et al., 2014; MacInnis and Gibala., 2016). For instance, multiple studies included in these meta-analyses concerning HIIT in older adults (Wu et al., 2021; Bouaziz et al., 2020) were training interventions of unknown or too low an intensity, with studies utilising training below 80% peak oxygen uptake ($\dot{V}O2_{peak}$) or 85% HR_{max}. Moreover, the meta-analysis by Wu et al (2021), also included interval exercise studies employing structured exercise plans with significant intra-intervention differences in exercise format throughout without objective verification of intensity (Ballesta-Garcia et al., 2019). This precipitates the need to appropriately isolate HIIT and SIT protocol-based research from practically and/or physiologically dissimilar protocols for systematic analysis.

2.1.2 Objectives

The objectives of this meta-analysis were to investigate the effects of HIIT interventions ≥ 2 weeks in duration in older adults, assessing for aerobic capacity, muscle power, muscle strength, body fat, and lean body mass.

2.2 Methods

2.2.1 Eligibility

This meta-analysis was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines. Studies that met the following criteria were included: (1) published as a full-text manuscript in English language; (2) not a review; (3) participants were a non-clinical population with a mean groups age ≥ 60 years; (4) studies were HIIT or SIT based protocols, with working intensities of either ≥80% HR_{max}, ≥80% maximal or peak aerobic capacity, or 'all-out' sprints of at least 15 s durations repeated a minimum of two times; (5) intervention period was ≥2 weeks; (6) reported at least one of: aerobic capacity, muscle power, muscle strength, body fat, or, LBM as an outcome variables. Additionally, descriptive data were required to be reported (e.g., sample size, mean, and standard deviation). Where this was not possible, data were requested from authors.

If studies split analysis between participants based on sex or training status, data were analysed separately. Where a study reported relative and absolute values for an outcome (e.g., aerobic capacity), only absolute values were included. However, for body fat, relative values were selected over absolute and where body fat was reported as total body and segmental, only the total body measurement was included. Where a study reported multiple separate outcomes for the

same variable, they were included as separate data sets. Where multiple outcomes for strength were reported, only isometric strength measurements were included where available, where isometric measurements were not available, the lowest isokinetic velocity measurement was included.

2.2.2 Information Sources

PubMed, ScienceDirect, and SPORTDiscus were searched with no start data, up until the 3rd of August 2020. The search was formed within all fields and terms were “high AND intensity AND interval AND training”, “interval AND training”, sprint AND interval AND training”, “high AND intensity AND training”.

2.2.3 Study Selection

The eligibility assessment was conducted by both authors in an unblinded and standardised manner. Once each database search was completed, duplicate studies were removed. Following which, all studies were downloaded into a single reference list. Titles and abstracts were screened for eligibility. Review articles were excluded, non-interval exercises, studies of clinical cohorts, studies with a mean age <60 years, and non-human studies were excluded. Full texts were downloaded for the remainder of the studies. Studies were read in full, studies were excluded for: only analysing clinical disease groups, when only non-eligible outcomes were reported, utilising protocols that were too low in physiological intensity, not being a HIIT or SIT intervention, intervention periods being <2 weeks in duration, and for not reporting the means. The remaining studies were assessed according to the PEDro scale (Maher., 2003). Studies were then coded for moderators of design method (randomised controlled trial (RCT) or uncontrolled trial (UCT)), exercise protocol, and eligible outcome measures.

2.2.4 Data Collection Process

Data were extracted for pre- and post-HIIT aerobic capacity, muscle power, muscle strength, body fat, and LBM. Two studies are enough to perform a meta-analysis, provided that those two studies can be meaningfully pooled and provided their results are sufficiently 'similar' (Cochrane Consumers and Communications Group; meta-analysis, 2016). In cases of missing data, means and standard deviations were estimated from using computer software (Image J, Maryland, USA, Image.net). The ascertained information was computed into a spreadsheet software (Jamovi, Version 1.6.2), and computed with a meta-analysis software extension (Jamovi Library, MAJOR, Version 1.1.1).

2.2.5 Data Items

Heterogeneity was quantified using the I^2 statistic (I^2). Heterogeneity was determined as low, medium, and high at 30%, 50%, and 75% respectively (Cochrane Consumers and Communications Group; meta-analysis, 2016). All analyses were performed using a Hedges random effects model. Data extracted from each study included study sample size, group descriptions, study design, pre- and post-intervention data, and where applicable, control means and standard deviations for eligible outcomes (aerobic capacity (**Figure 2.3.2**), muscle power (**Figure 2.3.4**), muscle strength (**Figure 2.3.6**), body fat (**Figure 2.3.8**), LBM (**Figure 2.3.10**)). Standard differences in means (SDM) were computed using the following equation (Higgins and Green, 2011):

$$SDM = (\mu_1 - \mu_2) \div \sigma$$

Whereby: SDM = Standard Difference in Means, μ_1 = treatment mean, μ_2 = control mean, and σ = pooled standard deviation. The following modification was made for UCT design studies, μ_1=

post-training value and μ_2= pre-training value. Where the SD for change between time points were not reported, it was calculated as below:

$$\sigma\ change = \sqrt{(\sigma_1^2\ +\ \sigma_2^2\ -(2\ \times corr\ \times\ \sigma_1\ \times\ \sigma_2\ ))}$$

Whereby: corr = correlation coefficient, σ_1 = SD change for pre-intervention, σ_2 = SD change for post-intervention. Correlation coefficients used depended on the outcome variable and were as follows, based on previous literature: aerobic capacity 0.916, muscle power 0.915, muscle strength 0.970, body fat 0.941, and lean mass 0.893.

2.3 Results

Study Selection

After the initial database search conducted on the 8th of September 2022, 2447 records were identified (**Figure 2.3.1**). Following removal of duplicates, 1737 titles and abstracts were screened for eligibility. 92 full text articles were assessed for eligibility, of which 17 articles were included for quantitative analysis. Of the 17 studies included, none were SIT studies, all were HIIT studies, of which 5 were randomised controlled trials (RCT) and 13 were uncontrolled trials (UCT) (**Table 2.3.1**). For all five outcome variables (aerobic capacity, muscle power, muscle strength, body fat, and LBM) publication bias was assessed using the trim and fill method for all five variables (**Figures 2.3.3, 2.3.5, 2.3.7, 2.3.9, and 2.3.11**) (Duval and Tweedie, 2000). The number of imputed studies was 4 for the outcome variable of body fat, and 0 for all other outcome variables.

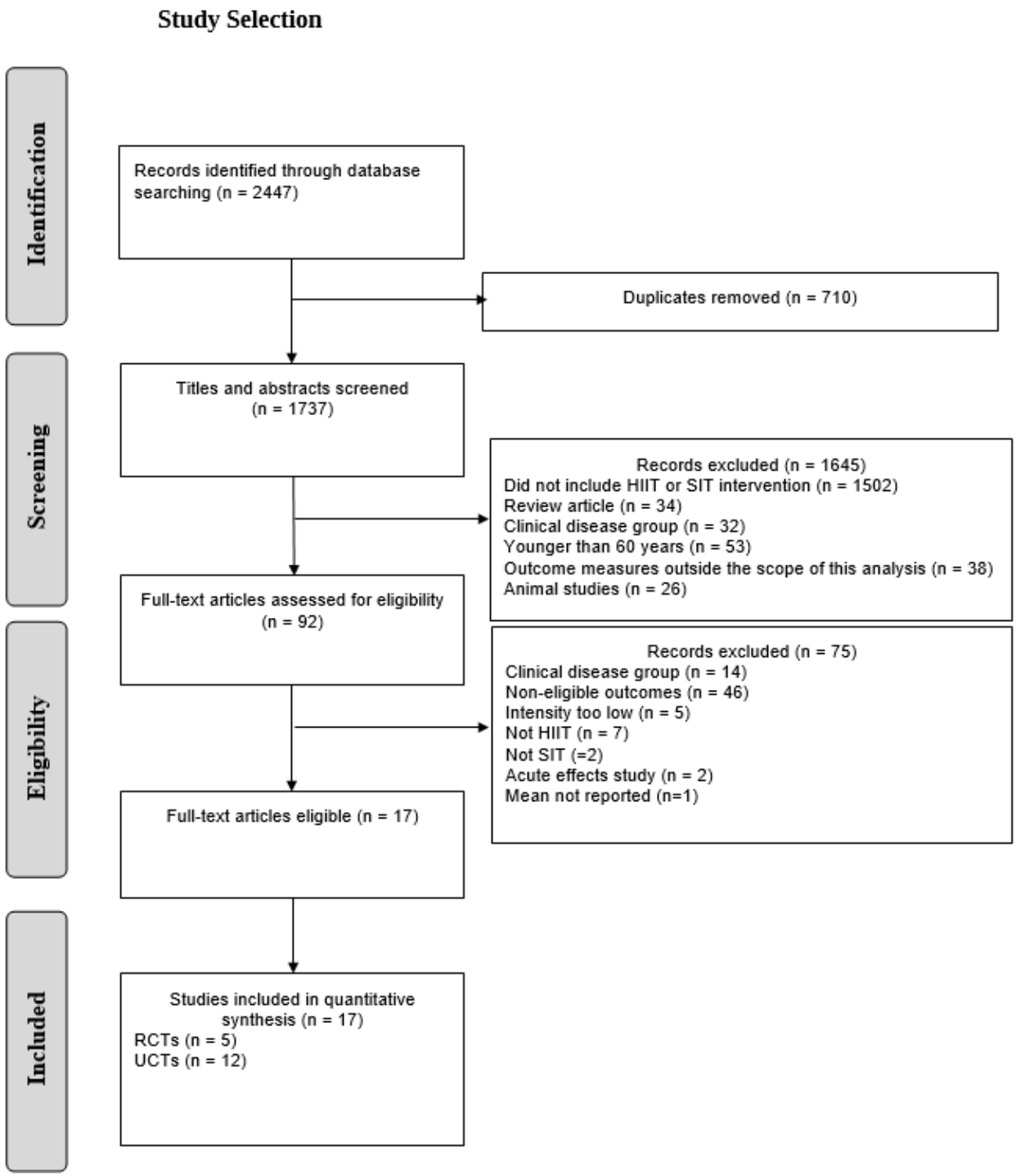


Figure 2.3.1 Schematic flow diagram describing exclusions of potential studies and final number of included studies**.** HIIT, high-intensity interval training; SIT, sprint interval training; RCT, randomised controlled trial; UCT, uncontrolled trial.

Study characteristics

Table 2.3.1 Description of the included HIIT studies and datasets.

Reference	Exercise Intervention	Study Duration	Design method	Outcome measures	Participants	PEDro score
Boukabous et al. 2019	Treadmill exercise: 6 x 1-minute intervals at 90% heart rate reserve interspersed by 2 minutes of active recovery three times a week	8 weeks	UCT	Aerobic capacity, muscle strength, body fat, lean mass	Obese women, mean age 66 years (minimum age 60 years, maximum age 75 years).	4
Bruseghini et al. 2015	Cycling, 7 x 2-minute intervals at 85-95% (maximal oxygen uptake) $\dot{V}O_{2max}$ interspersed by 2 minutes of recovery at 40% $\dot{V}O_{2max}$ three times a week	8 weeks	UCT	Aerobic capacity, muscle strength, body fat, lean mass	Healthy males, mean age 68 years (minimum age 65 years, maximum age 75 years).	3
Bruseghini et al. 2019	Cycling, 7 x 2-minute intervals at 85-95% $\dot{V}O_{2max}$ interspersed by 2 minutes of recovery at 40% $\dot{V}O_{2max}$ three times a week	8 weeks	RCT	Aerobic capacity, body fat	Healthy active males, mean age 69 years (minimum age 65 years, maximum age 75 years).	7
Grace et al. 2018	Cycling, 6 x 30 second intervals at 50% peak power output interspersed by 3-minute recovery at low resistance every 5 days	6 weeks	UCT	Aerobic capacity	1. Sedentary older men, mean age 62 years 2. Lifetime exercising older men, mean age 61 years	4

Herbert et al. 2017	Cycling, 6 x 30 second intervals at 40% peak power output interspersed by 3 minutes of active recovery every 5 days	6 weeks	UCT	Muscle power	Male masters' athletes, mean age 61 years	2
Herbert et al. 2016	Cycling, 6 x 30 second intervals at 40% peak power output interspersed by 3 minutes of active recovery every 5 days	6 weeks	UCT	Body fat, lean mass	1. Sedentary older men, mean age 62 years 2. Lifetime exercising older men, mean age 61 years	4
Hurst et al. 2019	Assorted multi and single joint exercise, 12–20-minute sessions with 3-minutes passive recovery between intervals, mean intensity 82% HR_{max}, and peak intensity of 89% HR_{max} performed twice a week	12 weeks	RCT	Aerobic capacity, muscle power, muscle strength	Older adults, mean age 62 years (minimum age 50 years, maximum age 81 years).	8
Hwang et al. 2016	All extremity ergometer, 4 x 4-minute intervals at ~90% HR_{max} with 3-minute recovery intervals at ~70% HR_{max} performed four times a week	8 weeks	RCT	Aerobic capacity, Body fat, lean mass	Sedentary older adults, mean age 65 years	5
Kim et al. 2017	All extremity ergometer, 4 x 4-minute intervals at ~90% HR_{max} with 3-minute recovery intervals at ~70% HR_{max} performed four times a week	8 weeks	RCT	Aerobic capacity	Sedentary older adults, mean age 65 years (minimum age 55 years, maximum age 79 years).	5

Knowles et al. 2015	Cycling, 6 x 30 second intervals at 40% peak power output interspersed by 3 minutes of active recovery every 5 days	6 weeks	UCT	Aerobic capacity	1. Sedentary older men, mean age 64 years 2. Lifetime exercising older men, mean age 62 years	3
Lepretre et al. 2009	Cycling, 6 x 1-minute intervals at ventilatory threshold two interspersed with 4-minute recoveries at ventilatory threshold one performed twice a week	9 weeks	UCT	Aerobic capacity, body fat	1. Older mean, mean age 65 years 2. Older women, mean age 66 years	2
Molmen et al. 2012	Treadmill running, 4 x 4-minute intervals at ~87% $\dot{V}O_{2max}$ interspersed by active recovery performed 3 times a week	12 weeks	UCT	Aerobic capacity	Older adults, mean age 72 years	1
Sculthorpe et al. 2017	Cycling, 6 x 30 second intervals at 50% peak power output interspersed by 3 minutes of active recovery every 5 days	6 weeks	RCT	Muscle power, body fat, lean mass	Sedentary older men, mean age 62 years (minimum age 56 years, maximum age 65 years).	6
Søgaard et al. 2017	Cycling, 5 x 1-minute intervals at ~130% W_{max} interspersed by 90 seconds recovery at low or no power output performed three time per week	6 weeks	UCT	Aerobic capacity, body fat, lean mass	1. Sedentary older females, mean age 63 2. Sedentary older males, mean age 63 Minimum age 55 years, maximum age 75 years for both groups.	3

Søgaard et al. 2019	Cycling, 5 x 1-minute intervals at ~130% W_{max} interspersed by 90 seconds recovery at low or no power output performed three time per week	6 weeks	UCT	Aerobic capacity, body fat, lean mass	Sedentary older adults, mean age 63 years, (minimum age 55 years, maximum age 75 years).	3
Støren et al. 2017	Treadmill or cycling, 4 x 4-minute intervals at ~90% HR_{max} with 3-minute recovery intervals at ~70% $_{max}$ performed three times a week	8 weeks	UCT	Aerobic capacity	1. Older adults, mean age 65 years 2. Older adults, mean age 74 years	2
Wyckelsma et al. 2017	cycling, 4 x 4-minute intervals at ~90% HR_{max} with 3-minute recovery intervals at ~55% HR_{max} performed three times a week	12 weeks	RCT	Aerobic capacity	Older adults aged 69 years (minimum age 65 years, maximum age 76 years).	6

Aerobic capacity

The overall standard difference in means (SDM) was for aerobic capacity following HIIT was 0.73 (p=0.001).

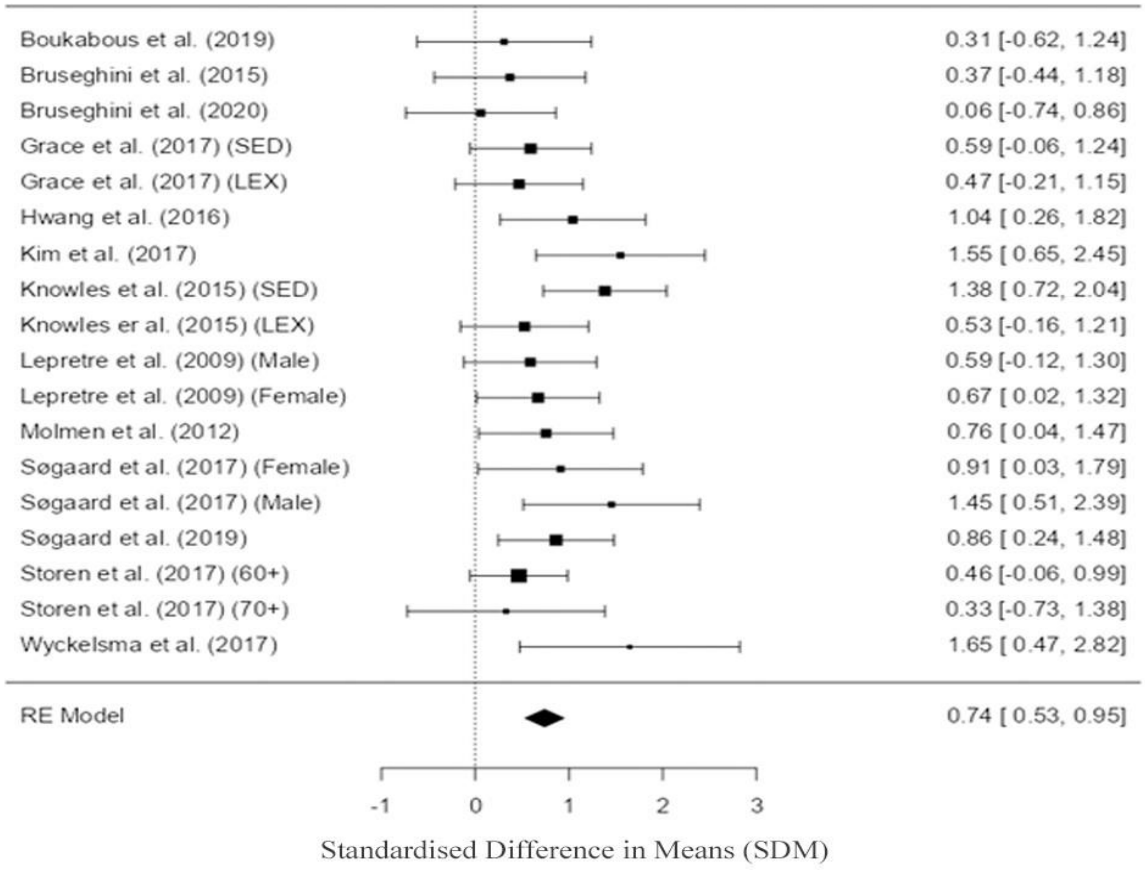


Figure 2.3.2 Summary of studies examining the effect of HIIT interventions on aerobic capacity. Studies are identified and reported with (left to right) authors name, (year of publication), and conditionally, where necessary, (designated group). The size of the filled square symbol for each study represents the weighting for the pooled SDM. SDM for each study are reported alongside upper and lower bounds 95% confidence intervals as SDM [upper bound, lower bound]. The

filled diamond indicates overall SDM. SED, sedentary; LEX, lifetime exercisers. 60+, 60–69-year-old group; 70+, 70 years and above group; RE, random effects. Positive SDM favours HIIT in increasing aerobic capacity compared with a control group or other exercise protocols.

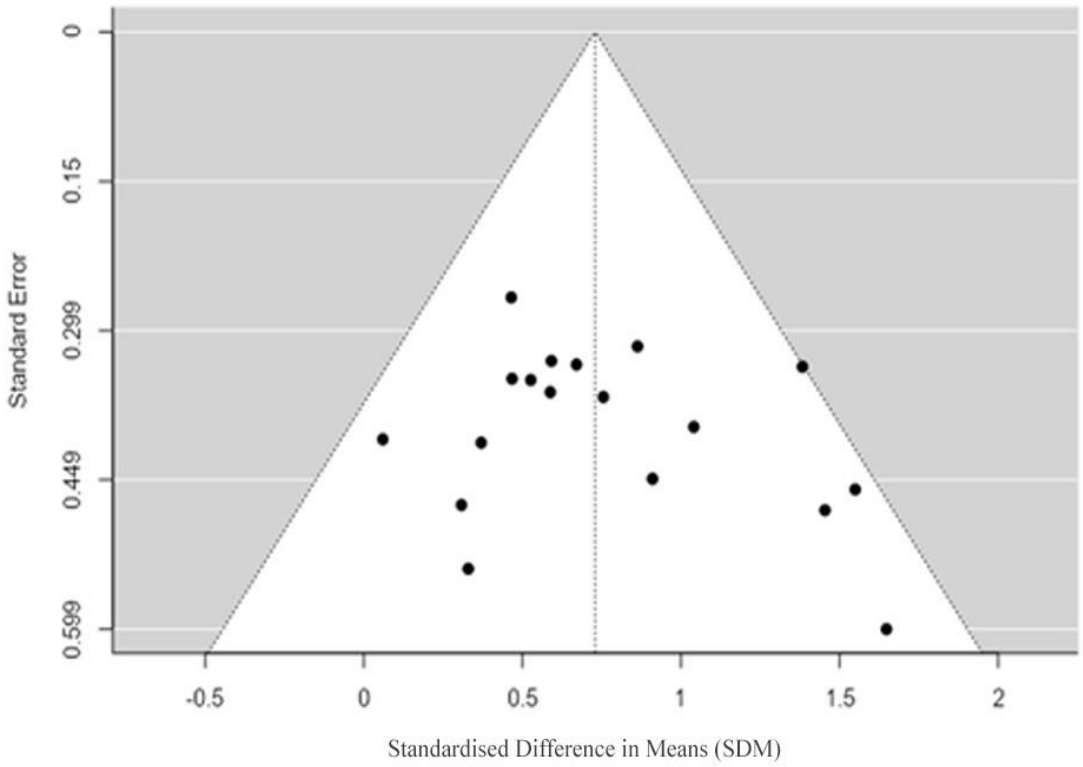


Figure 2.3.3 Funnel plot evaluating publication bias concerning the effect of high-intensity interval training on aerobic capacity, with SDM reported.

Muscle power

The overall SDM for muscle power following HIIT was 1.13 (p=0.014).

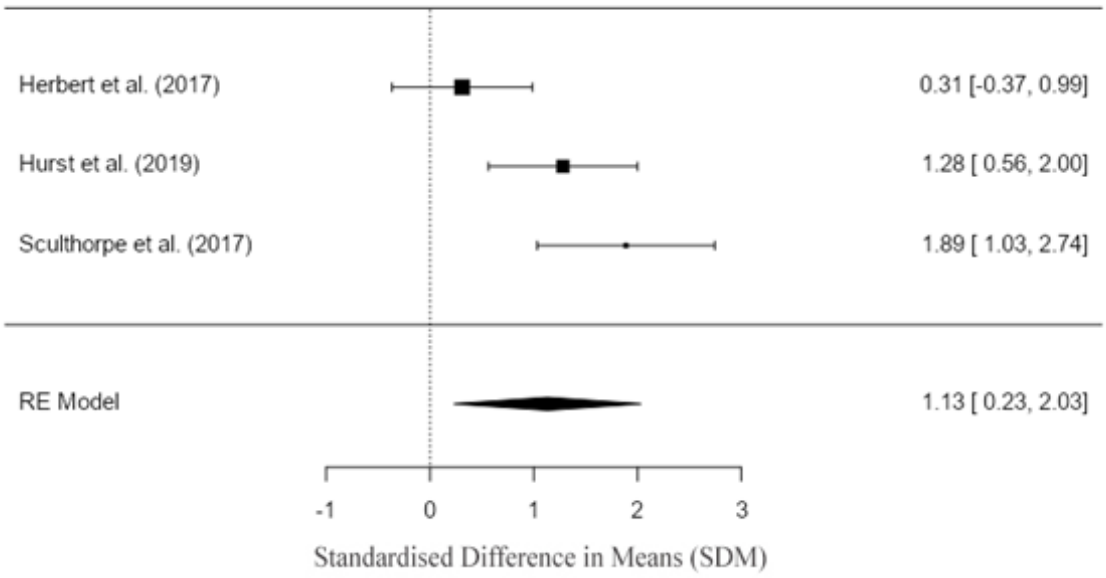


Figure 2.3.4 Summary of studies examining the effect of high-intensity interval training interventions on muscle power. Studies are identified and reported with (left to right) authors name, (year of publication). The size of the filled square symbol for each study represents the weighting for the pooled SDM. SDM for each study are reported alongside upper and lower bounds 95% confidence intervals as SDM [upper bound, lower bound]. The filled diamond indicates overall SDM. RE, random effects. Positive SDM favours HIIT in increasing muscle power compared with a control group or other exercise protocols.

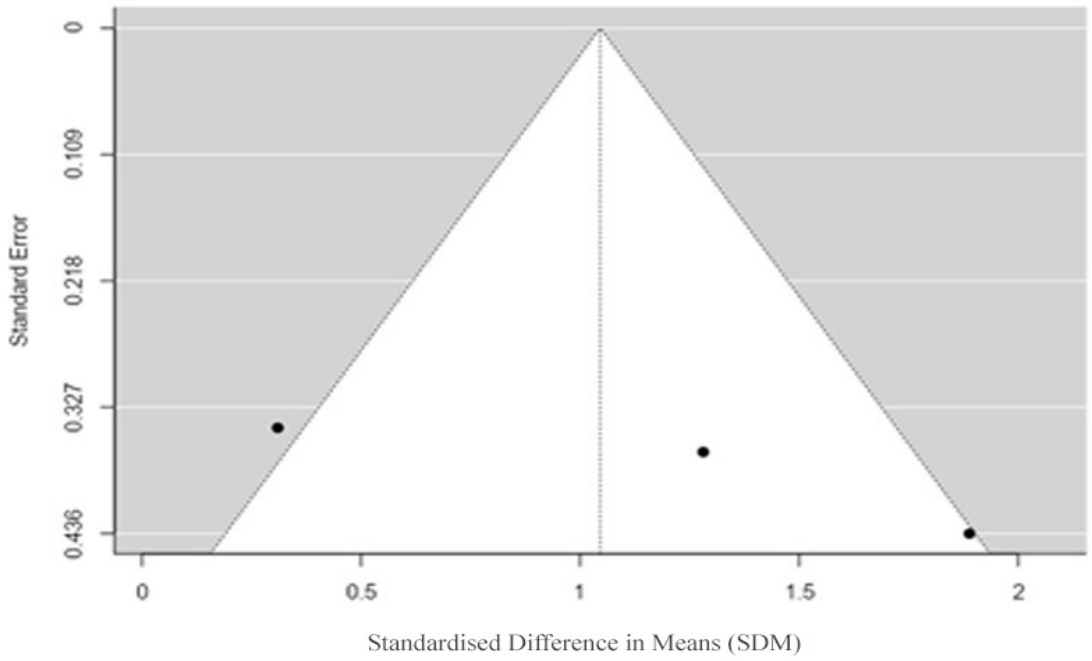


Figure 2.3.5 Funnel plot evaluating publication bias concerning the effect of high intensity interval training on muscle power with SDM reported.

Muscle strength

The overall SDM was higher for muscle strength following HIIT was 0.19 (p=0.308).

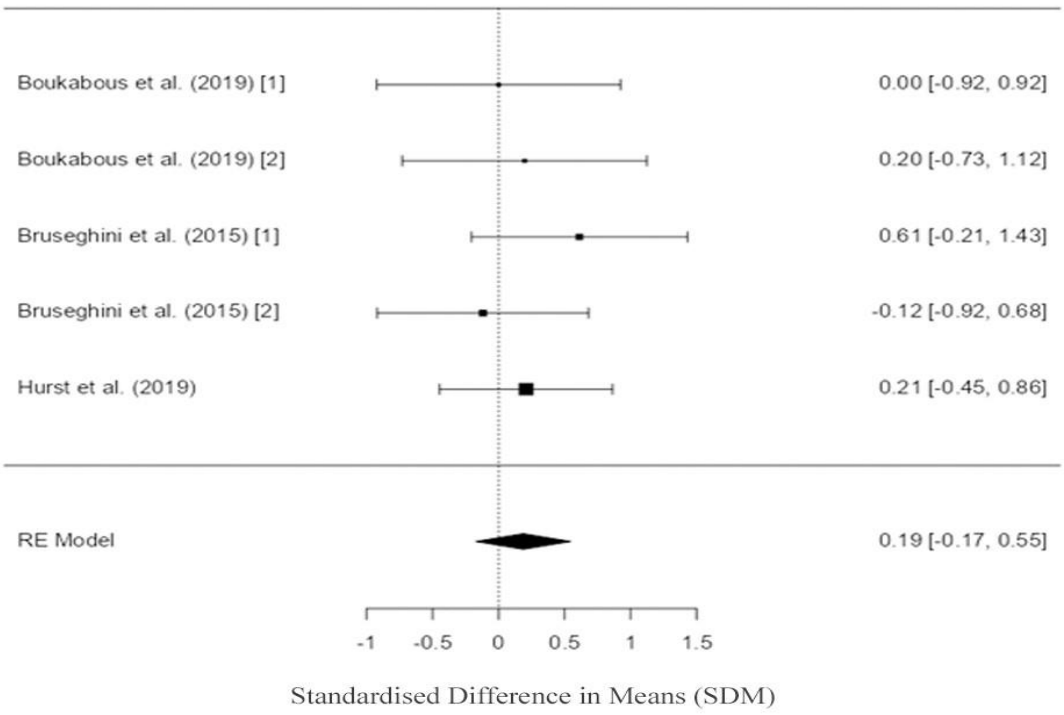


Figure 2.3.6 Summary of studies examining the effect of high-intensity interval training interventions on muscle strength. Studies are identified and reported with (left to right) authors name, (year of publication), and conditionally, where necessary, (designated group), and [1,2] indicates separate datasets. The size of the filled square symbol for each study represents the weighting for the pooled SDM. SDM for each study are reported alongside upper and lower bounds 95% confidence intervals as SDM [upper bound, lower bound]. The filled diamond indicates overall SDM. RE, random effects. Positive SDM favours HIIT in increasing muscle strength compared with a control group or other exercise protocols.

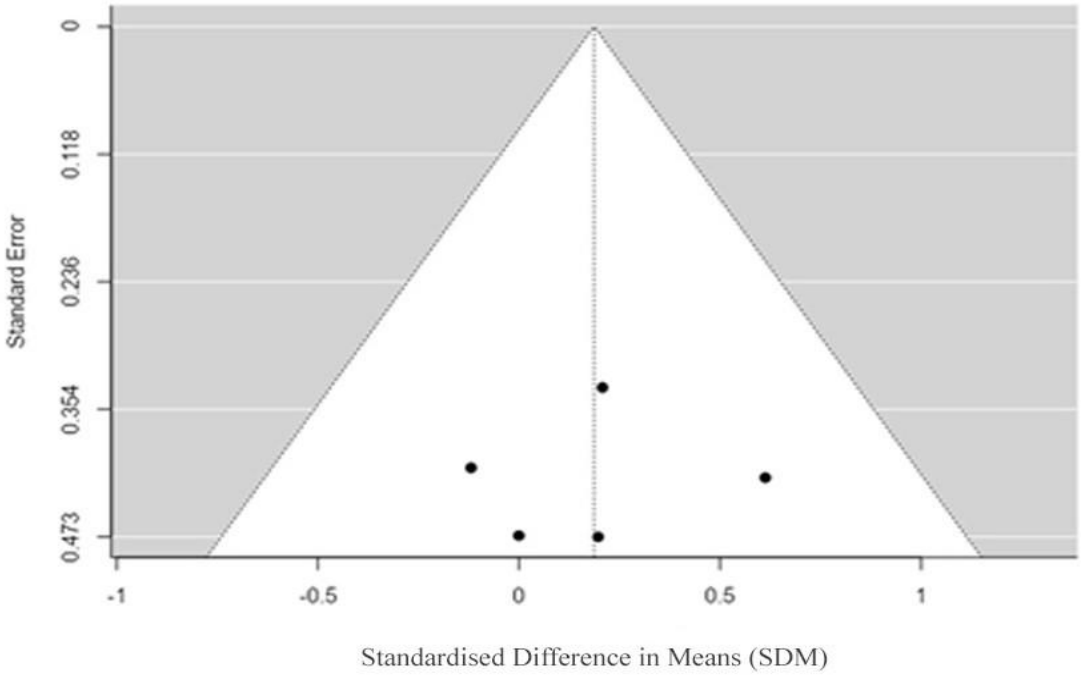


Figure 2.3.7 Funnel plot evaluating publication bias concerning the effect high intensity interval training on muscle strength with SDM reported.

Body fat

The overall SDM was lower for body fat following HIIT was -0.30 (p=0.004).

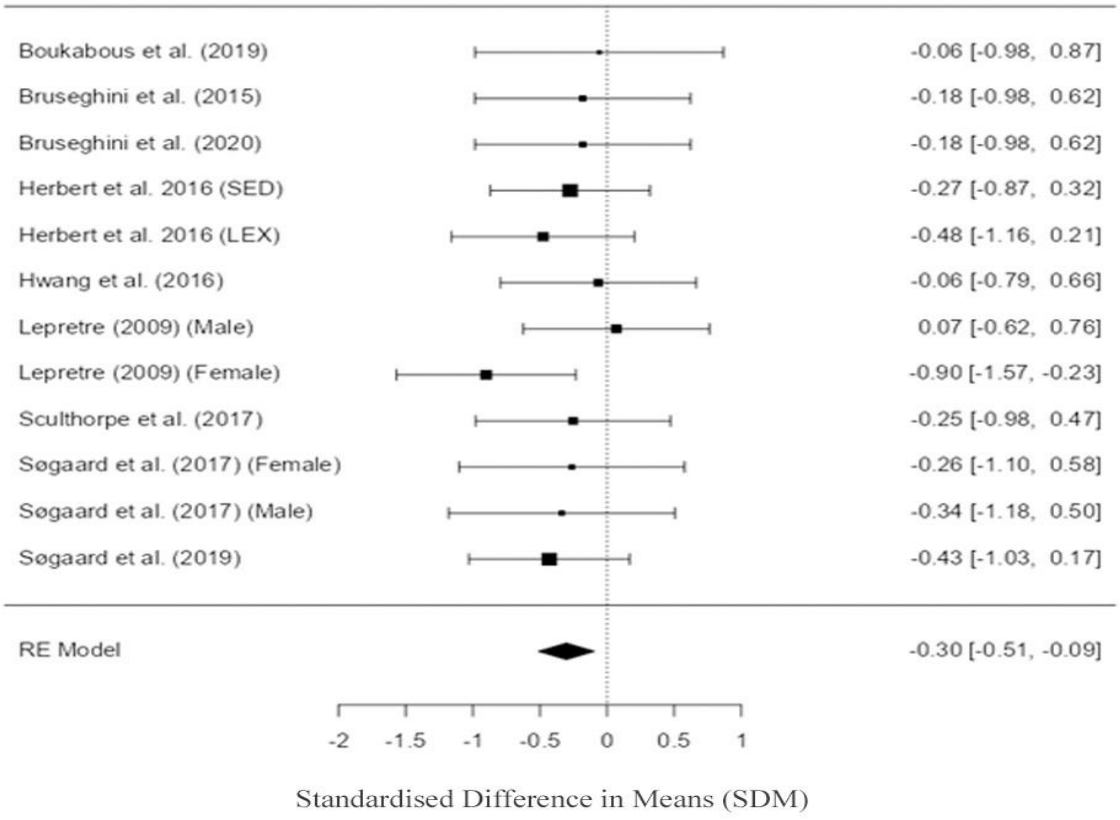


Figure 2.3.8 Summary of studies examining the effect of high-intensity interval training interventions on body fat. Studies are identified and reported with (left to right) authors name, (year of publication), and conditionally, where necessary, (designated group). The size of the filled square symbol for each study represents the weighting for the pooled SDM. SDM for each study are reported alongside upper and lower bounds 95% confidence intervals as SDM [upper bound, lower bound]. The filled diamond indicates overall SDM. SED, sedentary; LEX, lifetime exercisers; RE, random effects. Negative SDM favours HIIT in reducing body fat compared with a control group or other exercise protocols.

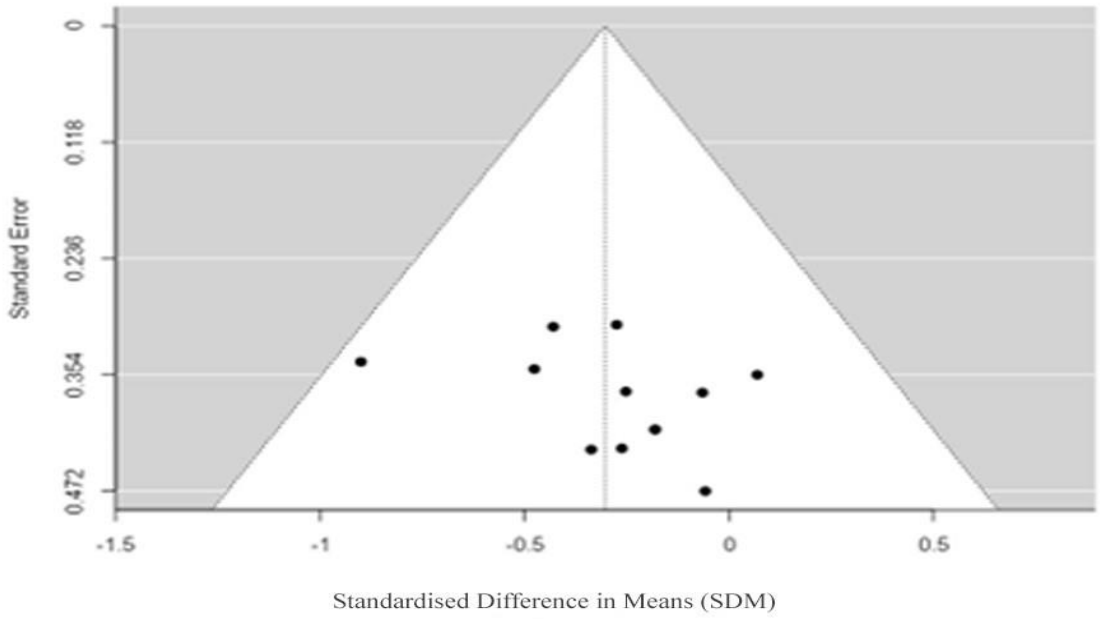


Figure 2.3.9 Funnel plot evaluating publication bias concerning the effect high intensity interval training on body fat with SDM reported.

Lean mass

The overall SDM was higher for lean mass following HIIT was 0.17 (p=0.150).

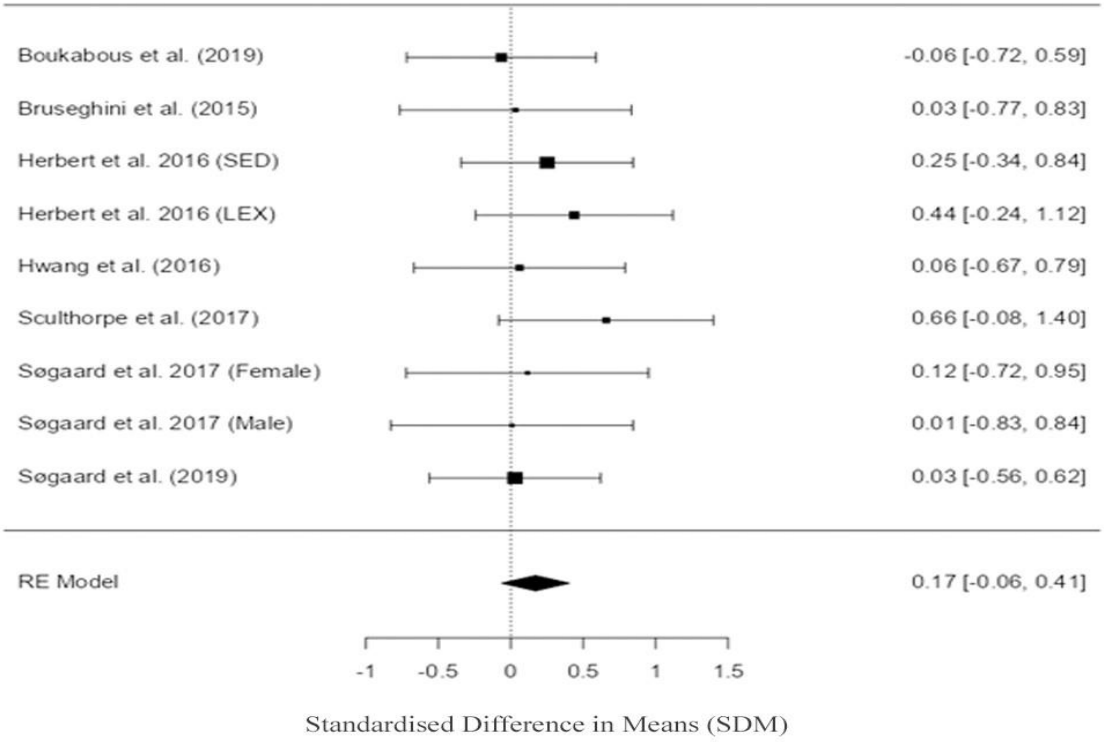


Figure 2.3.10 Summary of studies examining the effect of high-intensity interval training interventions on lean body mass. Studies are identified and reported with (left to right) authors name, (year of publication), and conditionally, where necessary, (designated group). The size of the filled square symbol for each study represents the weighting for the pooled SDM. SDM for each study are reported alongside upper and lower bounds 95% confidence intervals as SDM [upper bound, lower bound]. The filled diamond indicates overall SDM. SED, sedentary; LEX, lifetime exercisers; FE, random effects. Positive SDM favours HIIT in increasing lean body mass compared with a control group or other exercise protocols.

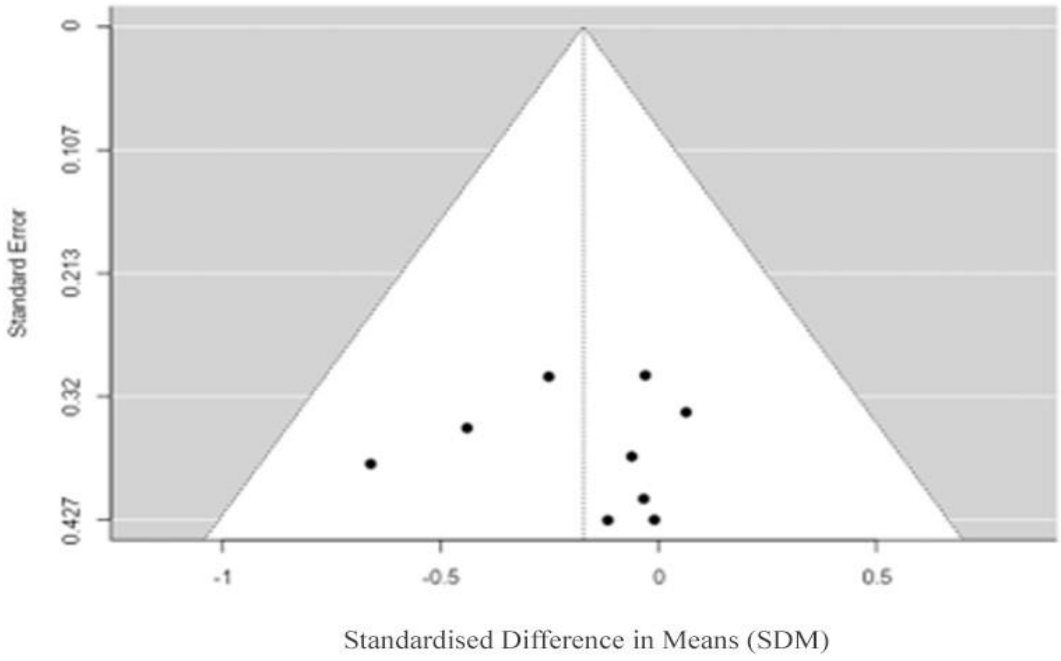


Figure 2.3.11 Funnel plot evaluating publication bias concerning the effect high intensity interval training on lean mass with SDM reported.

2.4 Discussion

The overall SDM in this meta-analysis demonstrated 6-12 weeks of HIIT in older adults yielded an increase in aerobic capacity (Figure 2.3.2), muscle power (2.3.4), muscle strength (2.3.6), and LBM (2.3.8), whilst decreased body fat was observed (Figure 2.3.10). This is consistent with the findings of Wu et al. (2021) despite Wu et al. (2021) conducting a meta-analysis with a broader range of studies, with equal or greater than 70% of heart rate maximum, alongside studies with ratings of perceived exertion (RPE) scale (Borg, 1982) between 11-13, which according to the modelling of Borg (1982) would equate to approximately 55 to 65% of maximal heart rate. This difference is best summarised by the difference in heterogeneity for studies included for the outcome of aerobic capacity, with an I^2 of 13.43 in the present study, vs Wu et al. (2021), which reported an I^2 of 74.6.

2.4.1 Aerobic Capacity

Analysis of the effects of HIIT on aerobic capacity revealed a relatively consistent increase, with all 18 studies demonstrating an increase compared with a control group or other exercise protocols (SDM = 0.74). It is noteworthy, however, that a difference in the SDMs of 1.59 were considerable, between the lowest SDM observed for the study by Bruseghini et al. (2020) and the highest for Wyckelsma et al. (2017). Studies with lower SDM increases utilised protocols with a various relatively low peak (90% heart rate reserve, 95% $\dot{V}O_{2max}$, 90% HR_{max}) and recovery (40% heart rate reserve, 40% $\dot{V}O_{2max}$, 70% HR_{max}) intensities (Boukabous et al., 2019; Bruseghini et al., 2015; Bruseghini et al., 2019; Storen et al., 2017). This indicates lower intensity HIIT may be less impactful compared with more intense HIIT. However, the study by Wyckelsma et al. (2017), employed a lower peak intensity protocol, and had the highest SDM increase amongst all studies.

Though the study intervention period was longer at 12 weeks, which only one other study replicates within the analysed datasets (Molmen et al., 2012). Although the protocols employed by Wyckelsma et al. (2017) and Molmen et al. (2012), are practically identical with both utilising a 4 x 4-minute interval protocols with similar intensities, ~90% of heart rate maximum vs ~87% of aerobic capacity, the study conducted by Wyckelsma had a higher SDM by 0.89. This inconsistency of outcomes is likely due to the baseline aerobic capacity of participants between the studies of with Molmen et al. (2012) conducting a study on participants with a mean $\dot{V}O_{2max}$ 35.0 ml.kg.min^{-1}, which was higher by approximately 10 ml.kg.min^{-1} when compared with Wyckelsma et al. (2017). This between-study observation corroborated with sedentary participants demonstrating increased SDMs when compared with trained counterparts in the two studies that compared for training status (Grace et al., 2017; Knowles et al., 2015). Interestingly, Hwang et al. (2016) and Kim et al. (2017), also utilised a lower peak intensity protocol, but with higher intensity recovery phases when compared with Wyckelsma et al. (2017), on participants with similar characteristics whilst increasing aerobic capacity similarly with an intervention period of only 8 weeks. Overall, this data indicates that the magnitude of training responses may be dependent on training duration, peak and mean intensity of the protocols, and the baseline fitness of participants.

Sex based differences between the studies were not coherent, with Lepretre et al. (2009) observing no considerable differences between the groups, whilst Sogaard et al. (2017) observed a 5% higher increase in the male group when compared to the female group. Although a 5% difference in means between sexes in the same study is considerable, studies with small sample sizes are at significant risk of bias to outlier values. Some potential indication is provided to this possibility when assessing the coefficient of variation ~4% and ~6% in female and males respectively, with the higher value for the male group suggestive of higher heterogeneity between

results. Moreover, it is noteworthy that the study by Storen et al. (2016) did not observe adaptive differences to HIIT between six age divided cohorts between 20-29 years to ≥70 years. Corroborating this finding are the two older group datasets from Storen et al. (2016), 60-69 years and the ≥70 years being analysed in the present study. This suggests that age does not seem to have a significant impact on aerobic capacity adaptations to HIIT.

2.4.2 Muscle Power

Only three studies were present in the current analysis for the effect of HIIT on muscle power (Herbert et al., 2017; Hurst et al., 2019; Sculthorpe et al., 2017). All three studies demonstrated a positive SDM, demonstrating consistency of outcome direction, compared with a control group or other exercise protocols (SDM = 1.13). However, between the Sculthorpe et al., (2017) and Herbert et al., (2017), there was a discrepancy of 1.58 in the SDMs. The training protocols, duration, and frequency were almost identical, barring a 10% higher peak power output (PPO) intensity being utilised by Sculthorpe et al., (2017) when compared with Herbert et al. (2017). Although, 10% differences in PPO may not seem significant, both Herbert et al. (2017) and Sculthorpe et al. (2017) measured PPO as relative to 'all-out' maximal efforts. In comparison, many research protocols define PPO aerobically, relative to maximal aerobic capacity. Importantly, for reference, research by Foster et al. (2015) in young adults observed an approximately 4-fold difference between 'all-out' PPO vs aerobically defined PPO. This would equate to a difference of approximately 40% between Herbert et al (2017) and Sculthorpe et al. (2017) if the PPO were aerobically defined. Although, this figure is not likely to extrapolate accurately, accounting for differences in age and fitness, it highlights the extreme magnitude of difference between the two separately defined PPO measures. And future research should aim to clarify by which measure they are defining PPO, as in many cases, descriptions are unclear and

rely on the reader to estimate which definition was used based on reference expectations for both ‘all-out’ PPO and aerobic PPO.

Training status of the participants, i.e., sedentary participants in the Sculthorpe et al. (2017) study, and masters athletes in the Herbert et al. (2017) study, likely influenced outcome, as a review by Hughes et al. (2018) postulated training responses to muscle performance are less in trained individuals, with greater magnitude of gains achieved in untrained individuals. In summary, it is likely training status (both in general, and HIIT-naivety) of participants has a large impact on outcome measures following HIIT, and it is possible that higher intensity protocols, defined by either aerobic PPO or ‘all-out’ PPO may have an impact on muscle power adaptations following HIIT.

2.4.3 Muscle Strength

The SDM for muscle strength was lower than that of muscle power, which is unsurprising as joint angular velocities combined with lower resistance protocols are more nurturing of muscle power adaptations than that of muscle strength adaptations (Akagi et al., 2020). Nevertheless, of the datasets utilised in the present analysis, seven out of nine datasets demonstrated increased muscle strength compared with a control group or other exercise protocols (SDM = 0.19). Boukabous et al. (2019) dataset [1] demonstrates a stagnant SDM to handgrip strength following a treadmill protocol. Boukabous et al. (2019), dataset [1], was derived using an upper limb measurement for the outcome of a lower limb-based intervention, which was unlikely to demonstrate adaptations, as adaptations to muscle strength are specific to the exercised muscle group, even where there may be strength cross education, it is limited to the homologous limb (Andrushko et al., 2018). In contrast, the Hurst et al. (2018) protocol utilised exercises of upper and lower limbs within the

same protocol, likely precipitating the improvement in strength observed, Moreover, the Boukabous et al. (2019) dataset [2] demonstrates an increase to muscle strength, measured as lower limb 1RM. Corroborating this, similar changes to isometric maximal voluntary contractions at a knee flexion angle of 60°, dataset [1], were observed by Bruseghini et al. (2015). Contradicting this, the Bruseghini et al. (2015), dataset [2], demonstrates a decreased SDM following HIIT when strength was measured at a knee flexion angle of 90°. Although it is difficult to speculate as to why the Bruseghini et al. (2015) datasets [1] and [2] differ, it is possible that the specificity of muscle strength adaptations were reflected differently between the measured knee flexion angles, as strength training adaptations are greatest at the exercised joint angles (Morrissey et al., 1995).

Although the general theory of exercise theorises the continuum of exercise across strength vs aerobic parameters (Hawley et al., 2014), previous reviews by Buchheit and Laursen (2013a) demonstrates the wide range of physiological adaptations that can be achieved with HIIT. Moreover, although aerobic training adaptations are usually not associated with muscular hypertrophy, this is an erroneous assumption, as aerobic training performed at higher intensities of approximately 70-80% HR_{max} have demonstrated potential to instigate muscle hypertrophic adaptations (Konopka and Harber, 2015). Importantly, all the studies analysed in the present meta-analysis utilised intensities higher than that proposed by (Konopka and Harber, 2015). Although muscle hypertrophy is not the only driver of muscle strength gain, it is a likely a contributor (Hughes et al., 2018; Taber et al., 2019). In summary, reports of increased muscle strength following HIIT in older adults are not entirely supported by data presented here. The small SDM and 95% CI spanning 0 suggest that if HIIT is capable of increasing muscle strength, this is inconsistent, and of a small magnitude.

2.4.4 Body Fat and Lean Body Mass

The present analysis demonstrates a negative SDM (-0.30) for body fat and a positive SDM (0.17) for LBM, compared with a control group or other exercise protocols. Data presented here suggest a consistent body fat lowering effect of HIIT, demonstrated by the moderate SDM and 95% CI not crossing 0. A smaller magnitude of effect, which did not reach the $P<0.05$ level, with 95% CI spanning 0 was observed for lean body mass. This is not entirely surprising as HIIT expends energy (MacInnis and Gibala, 2016), and has shown to blunt appetite in some populations (Afrasaybi et al., 2019; Thivel et al., 2012), which would promote loss of body fat. Conversely, although there are mechanistically feasible pathways by which HIIT may be anabolic (Callahan et al., 2021), data are not consistent in this observation.

Encouragingly, even without concurrent dietary controls or interventions alongside HIIT, most of the studies analysed observed decreased body fat and increased LBM, both being important facets of metabolic health (Abramowitz et al., 2018; Lee et al., 2018), with only two exceptions (Boukabous et al., 2019; Lepretre et al., 2009). It is noteworthy that during and immediately after exercise or training, muscle protein breakdown (MPB) is increased (Kumar et al., 2009). Thus, exercise and protein consumption need to be adequate to induce a net muscle protein synthesis (MPS) (Yang et al., 2012). Importantly, net MPS is the mechanism that is required to maintain or increase LBM in older adults to attenuate the potential for developing sarcopenia (Phillips, 2017). Moreover, previous research has theorised that anabolic resistance in older populations may be responsible for decreased muscle mass (Kumar et al., 2009). Therefore, Moore et al., (2015) postulate that, requirements for protein to maintain maximal MPS is 0.24 $g.kg^{-1}$ vs 0.40 $g{\cdot}kg^{-1}$ of body weight split over three daily meals for young and elderly men, respectively. It is prudent to assume that with an enhanced protein intake during HIIT studies, the LBM increase would be higher, and given the importance of avoiding sarcopenia, synergistic use of exercise, in particular

resistance exercise, and diet to manipulate body composition outcomes in research and practice will be of increased importance (Phillips, 2017).

2.5 Limitations and Future Research Directions

The key limitation in this meta-analysis is the lack of HIIT interventions studies in older adults measuring power output. This is particularly concerning, as a key health metric in ageing populations for maintaining independence and reducing all-cause mortality is muscle power, even more so than muscle strength (Byrne, 2016). Moreover, relatively few RCTs were present in the analysis. In our own acute response research during recruitment for the Yasar et al. (2019) study (Chapter 3), we found recruiting older adults for SIT to be challenging. It is prudent to assume most researchers investigating HIIT in older populations have and will continue to contend with this issue, as reflected by relatively low sample sizes included in the present meta-analysis. Therefore, a designated randomised control group can be prohibitive to the RCT model. Moreover, it is debatable whether relatively predictable effects to physiological variables such as aerobic capacity and muscle power amongst control participants are a worthy research price when forthcoming participants are likely sparse. Nevertheless, researchers should endeavor to implement an RCT model, or at least a 'waiting room' design with a control period to reduce type I error rates.

Results of our searches returned no SIT interventions, which presents a gap in the research literature that requires investigation, as SIT utilising ‘all-out’ efforts will likely simplify prescription and reduce time commitment, often cited as a barrier to exercise (Stutts, 2002; Trost et al., 2002). Moreover, SIT is reportedly efficacious as a training mode when adjusted appropriately (Milanovic et al., 2015; Vollaard and Metcalfe, 2017b).

2.6. Conclusion

Data presented here suggest HIIT in older adults has a health genic effect on aerobic capacity, muscle power, and body fat. For aerobic capacity, response to HIIT may be modulated by intervention duration, mean and peak intensity, and prior fitness of participants. Muscle power was the least measured outcome, but HIIT is seemingly effective at increasing muscle power. Muscle strength seems to be positively affected by HIIT, although the magnitude was smaller compared with muscle power. Body composition changes were positive, with body fat loss more prominent over lean body mass gain. Whilst there is suggestive evidence of positive effects on muscle strength and lean body mass, more data are required to confirm these observations, as these meta-analyses were limited by sample size, study controls, and overall study count. Therefore, more intervention studies are required of a higher sample size, quality of control and amelioration of contraindicating factors. Moreover, the HIIT protocols utilised in research need to reflect the practical requirements of the 'real world' by using easy to administer methods (i.e., without significant equipment needs, travel, specialist training, intensity monitoring, such as heart rate or power output).

Chapter 3: Study 1

3.1 Introduction

High-intensity interval training (HIIT) is characterised by exercise above 80% of maximum heart rate interspersed with lower-intensity recovery phases (MacInnis and Gibala., 2016). Sprint interval training (SIT), a derivative of HIIT, is characterised by maximal exertion, sustained for 30 s or less (Gist et al., 2014). HIIT has gained popularity due to improvements in fitness comparable to moderate-intensity continuous training (MICT) (Batacan et al., 2017; Gibala et al., 2012). Similarly, SIT has produced comparable adaptations to MICT in young adults (Burgomaster et al., 2008; Gist et al., 2014), including increased aerobic function, a key determinant of long-term mortality (Mandsager et al., 2018). With the reported increased enjoyment (Bartlett et al., 2011; Thum et al., 2017), and time efficiency (Gillen and Gibala., 2014), this supports promotion of HIIT or SIT over MICT, by removing potential barriers to exercise adherence.

A limitation of HIIT is that it requires intensity-based calculations (Buchheit and Laursen., 2013a; MacInnis and Gibala., 2016), which are not required in the use of 'all-out' SIT protocols. Previous HIIT research has shown effects indicative of improved health with three HIIT sessions per week, in a group with a mean age of 70 years (Robinson et al., 2017), and groups with a mean age of 63 years (Sogaard et al., 2018), and both 60–69 years and 70+ years (Storen et al., 2017). However, in other studies, similar benefits have been observed with a single session every 5 days, with a mean age range of 60 to 63 years (Grace et al., 2018; Hayes et al., 2017; Herbert et al., 2016; Sculthorpe et al., 2017). HIIT every five days has been found to increase peak power output (PPO) in older individuals with a mean age of 61 years (Herbert et al., 2017; Sculthorpe et al., 2017). PPO is a physiological measure of paramount importance to the older individual due to its importance in physical functioning (Byrne et al., 2016), which elevates the profile of HIIT as a training method to target improvement in power output. However, Herbert et al. (2015b) observed

a delayed recovery of PPO in older participants with a mean age of 63 years. The exercise protocol utilised was a HIIT session comprising of 6 × 30 second intervals working at 50% of PPO, interspersed with 3-minute active recovery phases. Therefore, some caution is required when prescribing HIIT to older adults. Moreover, it is possible that a delayed recovery in older individuals may transcend between HIIT and its derivative form of 'all-out' SIT, which employs a higher intensity.

Delayed recovery seen in older adults compared to their younger counterparts could be attributed to several biological processes (Lopez-Otin et al., 2013). The driver of the delayed response may be attributed to an age-associated reduction in mitochondrial function (Joseph et al., 2016). Consequently, a delayed recovery response may be initiated following exercise due to dysregulated reactive oxygen species production and regulation in ageing skeletal muscle (Vina et al., 2013). For a more detailed review of the mechanisms of skeletal muscle ageing, we suggest a previous review (Gomes et al., 2017). The primary effects of ageing on skeletal muscle are sarcopenia, defined as the loss of muscle, and dynapenia, defined as the loss of force production (Clark and Manini., 2010). Although the reduction of muscle strength and mass is a key determinant of physical function (Manini and Clark., 2012), muscle power may be a more important determinant of functional capacity (Byrne et al., 2016). Importantly, this decline in physical function is associated with increased incidence of physical disability, loss of independence, and increased mortality (Manini and Clark., 2012).

SIT has demonstrated positive power adaptations in young cohorts (Farzad et al., 2011; Kim et al., 2011; MacDougall et al., 1998; Weston et al., 2014; Whyte et al., 2010). This increase in power development appears to be maintained at low-volume SIT training loads of 4–6 repetitions of 10 s maximal sprints when compared to longer 30 s sprints in recreationally active young

adults (Hazell et al., 2010). Additionally, improvements have been observed in aerobic fitness with the prescription of SIT in young cohorts with Wingate SIT protocols consisting of 4–6 repetitions of 30 s maximal efforts (Cocks et al., 2013; Gibala et al., 2006). Interestingly however, even at significantly reduced training volumes (2 × 20 s sprints), SIT was effective at increasing aerobic function in young populations (Vollaard and Metcalfe., 2017a; Vollaard et al., 2017b). At present, there is a paucity of data concerning SIT in older adults.

The previously discussed literature justifies the investigation of a low volume SIT protocol as an intervention to increase overall physical function in older adults. However, before the adaptations to a 3 × 20 s 'all-out' SIT exercise training programme can be explored in older adults, it is imperative to know the duration of rest sufficient for post-training PPO recovery. A previous review has discussed literature on HIIT intersession recovery, concluding optimal recovery to be approximately 48 h following HIIT (Buchheit and Laursen., 2013b). However, research discussed in this review concerned young and athletic populations, who recover faster due to age-related biological factors (Joseph et al., 2016; Lopez-Otin et al., 2013; Vina et al., 2013). Therefore, the present study examined recovery periods utilised by Herbert et al. (2015b). This is important to avoid maladaptation, but also to avoid a period of reduced muscle power which, as previously discussed, would result in diminished functional capacity. Therefore, the aim of the present study was to investigate PPO after 3 days' and 5 days' recovery following a cycling SIT session in young and older participants. We hypothesised *a priori* that for PPO restoration, older participants would require 5 days' recovery, and young individuals would recover after 3 days.

3.2 Methods

3.2.1 Participants

This study was conducted in accordance with the Declaration of Helsinki and approved by the University of Cumbria Research Ethics Committee (Reference code: 16/74). Written informed consent was obtained from all participants prior to study commencement. A Physical Activity Readiness Questionnaire (PAR-Q) and American College of Sports Medicine (ACSM) pre-exercise participation screening were completed (Riebe et al., 2015). Participants were habitually physically active, exercising at least twice a week, totalling at least 150 minutes of moderate exercise. Nine older (6M/3F; mean age of 70 ± 8 years, height of 174 ± 9 cm, mass of 70 ± 10 kg) and nine young (6M/3F; mean age of 24 ± 3 years, height of 174 ± 9 cm, mass of 73 ± 7 kg) individuals participated. Participants abstained from alcohol, caffeine, and exhaustive exercise 24 hours prior to testing sessions.

Table 3.2.1.1 Basic information for the participants of the study 1

Participant characteristics		
	Young Participants	Old Participants
Height (cm)	174 ± 9	175 ± 9
Weight (kg)	73 ± 7	70 ± 10
BMI ($kg \cdot m^{-2}$)	24 ± 2	22.9 ± 3
Age (years)	24 ± 3	70 ± 8

Centimetres (cm); Kilograms (kg); Kilograms per square metre ($kg \cdot m^{-2}$)

3.2.2 Experimental design

On the first visit, a baseline PPO assessment was completed. Seven to ten days later, participants performed a SIT session. This exercise was followed by 3 days' rest or 5 days' rest in a randomised trial with a crossover design, after which they returned to complete a second PPO measure. Subsequently, participants returned 7–10 days later to complete the other arm of the study (i.e., SIT session with 3 days' or 5 days' recovery).

3.2.2 Session 1: Baseline Peak Power Output

Following measurement of stature and body mass, participants mounted the cycle ergometer, which was set up according to manufacturer's guidelines (Wattbike Pro, Wattbike Ltd, Nottingham, UK). Subsequently, participants warmed up for 6 minutes at approximately 70 W, interspersed with three ~2 s maximal sprints with an air brake resistance of 8 and a magnetic resistance of 1. Following 5 minutes of passive recovery, participants performed a 6 s Herbert test (Herbert et al., 2015a), which involved a maximal sprint from a stationary start, with the air brake set to 10 and magnetic resistance set to 1. Power output was calculated each second for the duration of the test, and PPO was considered as the highest value over 1 s.

3.2.3 Session 2 and 4: Sprint Interval Training and Peak Power Assessment

As above, participants warmed up for 6 minutes at approximately 70 W, interspersed with three ~2 s maximal sprints with an air brake resistance of 8 and a magnetic resistance of 1. Following 5 minutes of passive recovery, participants remounted the ergometer with the air brake resistance set to 3 and magnetic resistance set to 1. Participants completed 3 × 20 s maximal sprints, interspersed with 3 minutes of active recovery, with strong verbal encouragement during each sprint (Figure 3.2.3.1). A summary of work performed by participants is displayed in Table

3.2.3.1 Upon completion of the final maximal effort interval, a 5-minute self-paced cool down was performed. Following either 3- or 5-days' recovery, a Herbert 6 s test (Herbert et al., 2015a) was repeated to determine PPO.

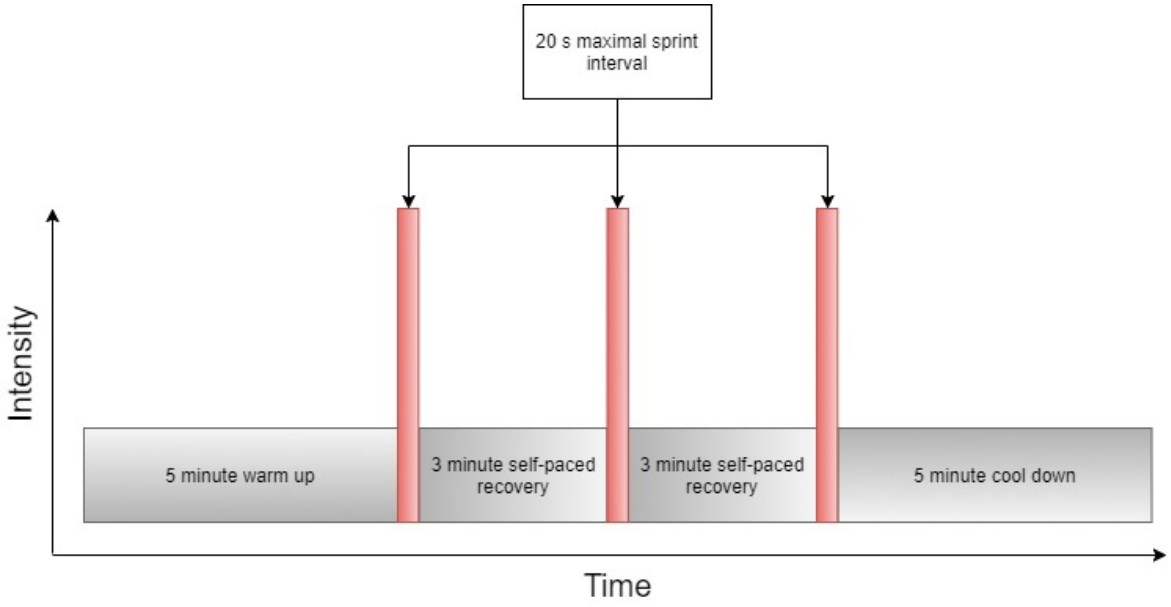


Figure 3.2.3.1 Schematic representation of sprint interval training protocol.

Table 3.2.3.1 Amalgamated peak and mean power completed by older and younger participants during the sprint interval training session. Data are reported as mean and standard deviation (SD).

	Peak Power (W)			**Mean Power (W)**		
Group	**Sprint 1**	**Sprint 2**	**Sprint 3**	**Sprint 1**	**Sprint 2**	**Sprint 3**
Older	541 ± 135	528 ± 139	498 ± 146	402 ± 93	384 ± 93	362 ± 88
Younger	897 ± 246	828 ± 219	788 ± 215	579 ± 139	513 ± 148	473 ± 156

3.2.4 Statistical Analysis

Statistics were processed using SPSS version 23.0 (IBM). Following a Shapiro–Wilk's test of normality and Levene's test for homogeneity of variance, a two-way repeated measures analysis of variance (ANOVA) (age (young vs. older) × recovery time (baseline, 3 days' rest, 5 days' rest)) was conducted. Alpha level was set *a priori* at $p < 0.05$. Partial eta squared (n^2_p) was used as a measure of main effect, defined as small 0.02, medium 0.13, and large 0.26. Cohen's *d* was calculated for pairwise comparisons. Additionally, an independent samples *t*-test was conducted to compare weekly mean habitual physical activity at above moderate intensity between older and young participants. Effect size was determined using Cohen's *d*, defined as small 0.1, medium 0.3, and large 0.5. Data are presented as means ± standard deviation (SD). No statistical power calculations were performed.

3.3 Results

A large age effect (p = 0.002, n^2_p = 0.460), small time effect (p = 0.702, n^2_p = 0.022), and medium interaction effect (p = 0.098, n^2_p = 0.135) was present for PPO. Younger participants produced greater PPO than older participants (Figure 3.3.1). Young PPO for baseline, 3 days' rest, and 5 days' rest was 942 ± 274 W, 921 ± 260 W, and 913 ± 258 W, respectively (Cohen's d < 0.11 for all pairwise comparisons). Older PPO for baseline, 3 days' rest, and 5 days' rest was 543 ± 151 W, 561 ± 152 W, and 555 ± 152 W, respectively (Cohen's d < 0.12 for all pairwise comparisons). Weekly mean habitual physical activity revealed a large effect between older (417 ± 313 minutes) and young participants (310 ± 65 minutes; t = (8.69) 1.01, p = 0.342, d = 0.68); equal variances were not assumed (p = 0.14).

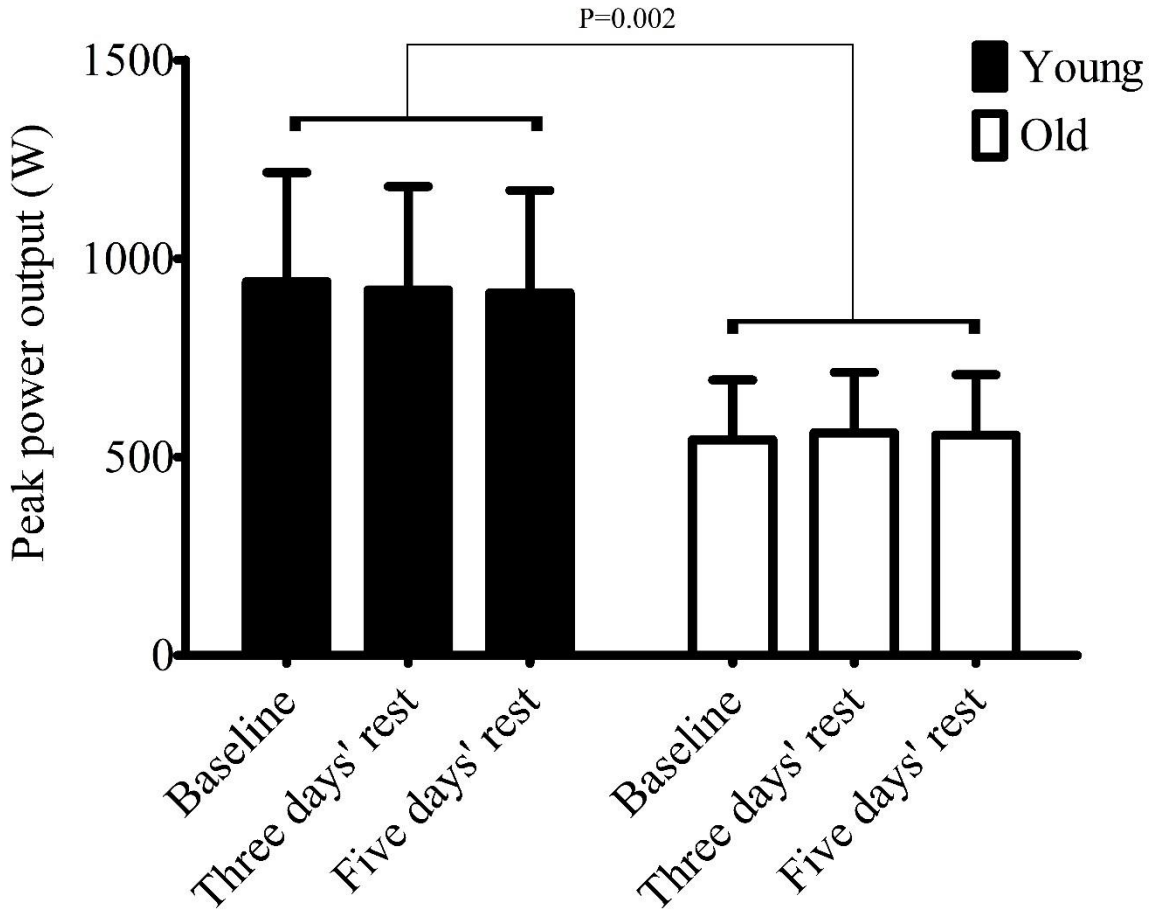


Figure 3.3.1 Peak power output (PPO) in young and older participants at baseline, after 3 days' rest, and 5 days' rest following sprint interval training (SIT). The alpha value of p = 0.002 indicates a significant difference between older and younger participants.

3.4 Discussion

The main finding of the present study was that young and older individuals recover PPO from a single SIT session after 3 days' rest. To our knowledge, this is the first study which has investigated recovery following SIT in older adults, and data presented here suggest that

recreationally active older adults can include SIT into their physical activity programmes with 3 days' rest, without detriments to PPO.

Current physical activity guidelines for older people suggest that at least 150 minutes of moderate, or 75 minutes of vigorous aerobic exercise should be accumulated weekly in at least 30- or 10-minute bouts, respectively (Chodzko-Zajko et al., 2009). Additionally, Chodzko-Zajko et al. (Chodzko-Zajko et al., 2009) suggested a resistance training frequency of twice per week. Currently, however, there is no comparable consensus on HIIT or SIT for older adults. Recent evidence has emerged in attempting to provide prescriptive guidelines for HIIT by Herbert et al. (2015b). This research demonstrated a delayed PPO recovery from HIIT in older males compared to young males (5 days versus 3 days respectively). Data from the present investigation differ from those of the HIIT-based recovery study by Herbert et al. (Herbert et al., 2015b) in that we have demonstrated PPO recovery from SIT after 3 days. This suggests that PPO recovery from HIIT and SIT are different in older adults.

The intensity of the protocol used in the present study was 'all out' or maximal power output, as opposed to the 50% of peak power output (~120% peak oxygen uptake), maintained for 30 s used by Herbert et al. (2015b). Given that a higher intensity was utilised in the present study, intensity is unlikely to be the determining factor in PPO recovery duration. The most obvious difference is the greater volume and duration of the exercise protocol employed by Herbert et al. (2015b). For instance, the present study used three 20 s maximal intervals, rather than six 30 s intervals at a sustained 50% of maximal effort (i.e., 60 s total work vs. 180 s total work). Previous observations have noted exercise, in particular aerobically intensive exercise, increases the production of reactive oxygen species (He et al., 2016). Mechanistic investigations suggest that reactive oxygen species are produced as a by-product of mitochondrial respiration, and reactive oxygen species

production is positively associated with oxidative phosphorylation (Austin et al., 2011). Additionally, previous research has noted the lower overall energy demand of low volume SIT protocols compared to typical HIIT protocols, even with consideration to the higher intensities used in SIT (MacInnis and Gibala., 2017). This suggests the possibility that the HIIT protocol employed by Herbert et al. (2015b) was more productive of reactive oxygen species in comparison with the 3 × 20 s SIT protocol used in the present study.

Excessive production of reactive oxygen species has been implicated in deleterious effects via inflammatory pathways to muscle function and performance (Powers et al., 2011). Although reactive oxygen species are facilitative of physiological adaptations, it is theorised that there is an optimal reactive oxygen species production threshold, influenced by exercise intensity and/or duration, which may be altered with training status (Steinbacher et al., 2015) and age (Vina et al., 2013). Given that the participants were of a similar training status and age in both the present study and the study conducted by Herbert et al. (2015b), we tentatively speculate that the training stimulus provided by a 3 × 20 s SIT protocol, as used in the present study, may be more appropriate for reactive oxygen species regulation, as opposed to the protocol used by Herbert et al. (2015b). However, this speculation requires further robust mechanistic evaluation within older age groups comparing HIIT and SIT protocols. Furthermore, it is noteworthy to mention that regular exercise that is aerobically intense has demonstrably improved ROS regulation (Steinbacher et al., 2015). Therefore, it is probable that ROS regulation would adapt with specific exercise habituation.

Strength training studies in older adults demonstrate two or three sessions per week are optimal to facilitate adaptions (Farinatti et al., 2013; Ferrari et al., 2013; Holviala et al., 2014). Similarly, recent evidence suggests that aerobic training adaptations are optimised at a frequency of 3 to 4

times a week in older adults (Huang et al., 2016). Strength training and aerobic training have been categorised as opposing ends of an exercise continuum (Hawley et al., 2014). However, prescribing from guidelines pertaining to either strength or aerobic training is not appropriate when considering the delayed recovery time associated with HIIT (Herbert et al., 2015b).

Higher-frequency HIIT in older adults with a mean age of 63 years performed thrice weekly has increased peak oxygen uptake by 3% and 7% for women and men, respectively, over 6 weeks (Sogaard et al., 2018), approximately 11% for both 60 to 69 and 70 and above age groups over 8 weeks (Storen et al., 2017), and approximately 16% over 12 weeks (Robinson et al., 2017). However, a similar magnitude of improvement was observed, approximately 11% and 8% for previously sedentary and lifetime exercisers with a mean age range of 60–63 years, respectively, utilising lower-frequency HIIT performed once every 5 days for 6 weeks (Grace et al., 2018). Importantly, only studies employing lower-frequency HIIT in older individuals have recorded PPO, with increases of approximately 17% in previously sedentary individuals with a mean age of approximately 62 (Sculthorpe et al., 2017), and 8% in master athletes with a mean age of approximately 60 years (Herbert et al., 2017). These data suggest lower-frequency HIIT may optimise aerobic improvements whilst increasing power in older individuals. Although strength and power are different variables, it is noteworthy to mention that the study by Robinson et al. (Robinson et al., 2017) did not observe any increases to leg press strength following high-frequency HIIT training in older adults with a mean age of approximately 70 years.

Previous research by Adamson et al. (Adamson et al., 2018) demonstrated that repeated (6–10 repetitions) ×6 s sprints increased power by ~13 % in an older cohort with a mean age of approximately 66 years, at a frequency of twice per week over a 10-week training intervention. This suggests that neurological adaptations are likely to be well targeted by shorter sprints.

However, longer durations of 20 s are associated with increased metabolic stress, which is associated with increased mitochondrial biogenic messenger ribonucleic acid (mRNA) responses when compared to a work matched protocol consisting of shorter 5 s sprints (Fiorenza et al., 2018). This suggests that longer sprints are better optimised to increase aerobic function, which decreases overall mortality risk (Mandsager et al., 2018). Due to the divergent stimulus provided by shorter sprints, previous reviews on the topic have justifiably differentiated this type of training as repeated sprint training (RST) (Buchheit and Laursen., 2013a). Therefore, at present, we are unaware of any research regarding SIT in older individuals.

We acknowledge the present study is not without limitations. For example, the use of recreationally active older adults was used in the current investigation, which does not permit application of these results to sedentary older adults. However, this recruitment strategy was necessary to ensure safe participation of older participants during maximal exercise (Riebe et al., 2015). Yet, HIIT has been used effectively in rehabilitation programmes for clinical populations in respiratory (Guadalupe-Grau et al., 2017) and cardiac (Nilsson et al., 2008) pathologies, therefore demonstrating efficacy in 'higher-risk' cohorts. Importantly, the current findings may not translate to different modes of exercise, e.g., running, due to the associated increase in eccentric loading (Bijker et al., 2002), which may increase recovery duration from exercise. Therefore, an investigation into recovery from different formats of sprint interval training is justified, with a particular focus on eccentric vs. concentric exercise load. Furthermore, the use of mixed gender sampling decreases the homogeneity of the groups included in the study.

3.5 Conclusion

In conclusion, the results of this study suggest that PPO recovery is similar between older and young adults after 3 days' rest following SIT. These data permit SIT prescription in older adults, in the knowledge that recreationally active individuals will be recovered after 3 days' rest. We believe these data can guide SIT prescription in active older individuals who may perform SIT following 3 days' rest. As a strength of SIT over HIIT is that prescription is uncomplicated, future research may consider practically applicable modes of SIT in older adults, and whether SIT is a viable intervention to improve physical functioning.

Chapter 4: Study 2

4.1 Introduction

The previous chapter intimated older adults recover from sprint interval training (SIT) after three days. Given this information older adults can perform SIT every three days without prolonged fatigue. However, as the experiment in chapter 3 was completed on a cycle ergometer, it is of practical importance to determine whether other forms of SIT which remove some barriers to exercise (i.e., specialised equipment) are comparable in terms of acute response.

The benefits of physical activity, formal or otherwise, to human health are widely documented in exercise science literature and beyond (Hawley et al., 2014). However, most individuals do not adhere to guidelines to exercise (Hunter et al., 2014). Consequently, this facilitates the development of a functionally debilitating health deficit, particularly in old age, with diseases such as sarcopenia, osteoporosis, alongside several cardiovascular pathologies (Mora and Valencia, 2018).

The frequency, intensity, duration, and type of physical activity have clear effects on the outcomes of exercise (Burnet et al., 2019; Power and Clifford, 2013). As such, modifications to physical activity require careful consideration and individuals undertaking physical activity need to ensure optimal physical activity prescription for their individual needs. i.e., age, gender, physical capital, and training experience (Piercy et al., 2018). Thus, physical activity does not have a uniform approach suitable for everyone.

At present the American College of Sports Medicine (ACSM) suggests a combination of physical activity, ranging from aerobic training to resistance training for older adults (Chodzko-Zajko et al., 2009). Both aerobic and resistance training stimulate different adaptive processes, resulting in divergent adaptations (Hawley et al., 2014). However, despite evidence in support of physical

activity improving health, many of these recommendations are not being achieved in developed nations (Hunter et al., 2014; Tremblay et al., 2011; Tucker et al., 2011). For instance, Strain et al. (2016) observed that approximately 75% of 65–74-year-old individuals, and 87% of over 75-year-old individuals do not partake muscle strengthening activities, with similar figures reported for balance and co-ordination exercises. This has proliferated investigations into barriers to exercise, whether logistical, psychological, or financial (Johnson et al., 1990; Lees et al., 2005; Myers and Roth, 1997; Schutzer and Graves, 2004). Consequently, there is an increasing interest in adapting exercise to reduce these barriers (Allison et al., 2017; Bartlett et al., 2011; Gillen and Gibala, 2014).

High intensity interval training (HIIT) has been suggested as a training method able to reduce the time burden of achieving physical activity targets (McCarty et al., 2019). HIIT utilises periods of high intensity exercise, usually above 85% of an individual's maximal oxygen uptake ($\dot{V}O_{2max}$), interspersed with periods of recovery (MacInnis and Gibala, 2016). This differs from the commonly promoted aerobic training method referred to as moderate intensity continuous exercise (MICT), which requires an exercise intensity of approximately 50 - 75% of $\dot{V}O_{2max}$ (Hannan et al., 2018). Currently, evidence suggests that if high intensity activity is adopted, it may halve the weekly requirement of aerobic activity from 150 to 75 minutes (Chodzko-Zajko et al., 2009). Corroborating this suggestion, a meta-analysis comparing HIIT and MICT found both forms of training equal at increasing older adults' $\dot{V}O_{2max}$ (Hwang et al., 2016). In older populations, HIIT is an effective form of training for increasing both aerobic and anaerobic measures in performance (Knowles et al., 2015; Sculthorpe et al., 2017). Importantly, this reduces likelihood of disease, ill-health, and all-cause mortality, increasing both an individual's lifespan and health span (Byrne et al., 2016; Laukkanen et al., 2016).

Sprint interval training (SIT) is a sub-category of HIIT, with the key difference being that SIT requires supra-maximal effort > 100% $\dot{V}O_{2max}$, rather than the typically observed intensities during HIIT, which typically require effort < 100% $\dot{V}O_{2max}$ (MacInnis and Gibala, 2016). Often, the instruction given to participants during SIT participation is to exert 'all-out' effort (Gibala and Hawley, 2017). This clarifies requirements for participants, without the need for ergometers or heart rate monitors, increasing the practicality of SIT prescription. A popularised form of SIT, marketed as the 1-minute workout has been demonstrated to be effective at increasing $\dot{V}O_{2max}$ (Gillen et al., 2014). The 1-minute concerns the 3 x 20 seconds of 'all-out' effort, which is often interspersed by two to three minutes of recovery. The evident decrease in time and volume commitment when compared to MICT and HIIT protocols whilst maintaining comparable endurance adaptations is worthy of research attention (Gillen et al., 2016; Gist et al., 2014; Sloth et al., 2013; Vollaard and Metcalfe, 2017). Moreover, research conducted by Vollaard and Metcalfe (2017b), demonstrates SIT is perceived to be easier than common HIIT protocols. High perceived difficulty is often cited as a significant barrier to adoption of adherence to exercise protocols (Ekkekakis et al., 2011). Therefore, avoiding high perceived difficulties increases the likelihood of adoption and adherence to SIT, by being demonstrably more tolerable.

To date, much research on HIIT and SIT has utilised treadmills and cycle ergometer protocols (Batacan et al., 2016; Gist et al., 2013), likely due to the ease of monitoring and quantifying workloads for research purposes. However, providing the public with low-cost, and practical forms of training are likely to have a significant impact on the uptake and useability of SIT. Static sprinting and stepping are forms of exercise that are potentially suitable to SIT protocols, with the format of the exercise allowing for maximal effort and submaximal recovery phases without necessity for specialist equipment to measure power or effort output. Stair climbing SIT increases cardiorespiratory fitness in previously untrained young women (Allison et al., 2017).

Fundamentally, stepping and stair climbing demand a similar physical movement pattern, however, 'stair-sprinting' may present an unacceptable level of risk in older adults. This necessitates further research on stepping SIT in older adults, which may present a safer alternative. Previous research in cycling vs running research suggests that there are differences pertaining to demands of both exercise modes (Bijker et al., 2002). Bijker et al. (2002) identified key differences between eccentric vs concentric loading, with cycling exhibiting greater volume of concentric contractions. Moreover, load bearing requirements of running exercise are not present in cycling exercise, which may interfere with physiological demands (Bijker et al., 2002; Stewart and Hannan, 2000). Therefore, it is clear cycling and running present different acute physiological responses.

As previous data suggests practically applicable SIT is cardioprotective in the young (Allison et al., 2017), it would be of interest to examine this phenomenon in older adults. Yet, whether this form of SIT is comparable in terms of acute physiological response to the more commonly studied cycle ergometry SIT is unknown, particularly in older adults. As such, the primary aim of this study was to compare three different SIT modes (stationary cycling, static sprinting, and box stepping) for physiological and perceptual markers of exercise intensity, and exercise enjoyment. It was hypothesised *a priori* that $\dot{V}O_{2peak}$, peak blood lactate concentration BLa_{peak}, peak heart rate, perceived exertion, and enjoyment would be different between exercise modes (static sprinting, cycle ergometry, and box stepping).

4.2 Methods

4.2.1 Participants

This study was carried out in accordance with the Declaration of Helsinki and approved by the University of Cumbria Ethics Committee (Reference code: 16/74). Participants were 11 healthy older adults (8 males and 3 females). Males age ranged from 61-84 years of age (70 ± 7 years of age, height 176 ± 7 cm, mass of 76 ± 12 kg, and a body mass index (BMI) of 24 ± 4 $kg{\cdot}m^{-2}$). Females age ranged from 62-69 years (65 ± 4 years of age, height of 162 ± 6. cm, mass of 58 ± 9 kg, and a BMI of 22 ± 5 $kg{\cdot}m^{-2}$). Participants were habitually physically active, with a pre-study physical activity of 350 ± 141 $min{\cdot}wk^{-1}$ equal to or above a moderate intensity. Abstention from alcohol, caffeine, and exhaustive exercise was required for 24 hours prior to testing sessions. Participants were asked to maintain dietary and physical activity habits throughout the study. Participants replicated their dietary intake for all sessions from 22:00 h the previous evening.

Table 4.2.1.1 Basic information for the participants of the study 2

Participant characteristics		
	Male Participants	Female Participants
Height (cm)	176 ± 7	162 ± 6
Weight (kg)	76 ± 12	58 ± 9
BMI ($kg{\cdot}m^{-2}$)	24 ± 4	22 ± 5
Age (years)	70 ± 7	65 ± 4

Centimetres (cm); Kilograms (kg); Kilograms per square metre ($kg{\cdot}m^{-2}$)

4.2.2 Experimental Design

Participants attended four sessions in total, with the first being a familiarisation session. Subsequently, participants completed the three exercise modes (static sprinting, stationary cycling, box stepping) in a randomised trial, with a counterbalanced study design. Laboratory visits were 5-7 days apart. Postural sway was determined 2 min prior to-, 2 min post-, 10 min post-, and 20 min post-exercise, for each SIT mode.

4.2.3 SIT Protocol

The SIT protocol was consistent with chapter 3 (study 1) in that each mode consisted of a 3 min self-paced warm up, followed by three maximal 20 s sprints, interspersed by 3 min self-paced recovery. Following completion of the final interval, a self-paced cool-down was undertaken for 3 min (Figure 4.2.9.1). Strong verbal encouragement was provided for all sprints.

4.2.4 Static Sprinting

Static sprinting was performed inside a 1 m square area, with white tape outlining the edges for easy identification. Participants sprinted in the space as fast as perceptually possible with minimal frontal or lateral movement, with dynamic positional adjustments requested by the lead researcher as required. Peak foot height was encouraged to be approximate to the participants' knee height.

4.2.5 Cycle Ergometry

Participants mounted a cycle ergometer, previously adjusted to fit in accordance with the manufacturer's guidelines (Wattbike Pro, Wattbike Ltd, UK). The cycle ergometer air brake resistance was set to 8, and the magnetic resistance was set to 1. Participants remained seated for the duration of the SIT protocol and exerted maximal effort during sprints.

4.2.6 Box Stepping

An exercise step (Reebok Professional Step, Reebok Ltd, USA) was placed in front of participants at a height of 20 cm. Participants stepped on and off the step as fast as possible during each 20 s sprint. A spotter was present during sessions to ensure safe participation.

4.2.7 Familiarisation

Participants had their height, mass, and body mass index (BMI) measured using an ultrasonic measuring station (SECA 287, SECA, Germany). Participants then warmed-up on a cycle ergometer for 5 min at a self-defined intensity. Subsequently, following demonstration from the lead researcher, participants performed a single 20 s bout of each exercise mode, interspersed by 3-minutes of self-paced rest, which was followed by 3 cool-downs.

4.2.8 Physiological Intensity Assessment

Peak oxygen uptake ($\dot{V}O_{2peak}$) was determined using a Cortex 2 Metalyser 3B-R2 (Cortex, Biophysik, Leipzig, Germany). Expiratory airflow was achieved using a volume transducer (Triple V Turbine, Digital) connected to an oxygen (O_2) analyser. The Metalyser was calibrated according to manufacturer's guidelines prior to each test. After being switched on for 60-minutes, the O_2 and carbon dioxide (CO_2) sensors were calibrated against environmental air in addition to reference gas from a canister with a composition of (5% CO_2, 15% O_2, and 80% N_2). Air volume calibration was achieved by reference air strokes using a 3-litre pump. A chest strap monitor was attached to participants' chests with heart rate measured continuously throughout the test (Polar F1, Polar, Finland). Prior to each sampling of blood lactate, participants' index finger was disinfected using an alcohol-based wipe. Laceration was achieved with the use of a lancet, extracting a droplet of blood from the fingertip which was then sampled with a blood lactate

analyser (Lactate Plus, Nova Biomedical, UK). Resting blood lactate was sampled in a stationary position for each of the respective exercise modes. Oxygen consumption and heart rate were recorded throughout the SIT session to obtain $\dot{V}O_{2peak}$ and peak heart rate, respectively. Further blood lactate samples were collected 5-10 s after each sprint, and a final sample collected immediately following the 3 min cool down to obtain peak blood lactate, $\dot{V}O_{2peak}$ data was extracted and processed using a spreadsheet (The Document Foundation, Germany). $\dot{V}O_{2peak}$ was calculated as the peak value observed, using a 10s moving average.

4.2.9 Psychometric and Perceptual Assessment

Participants rated their perceived exertion prior to SIT and following each sprint on a 10-scale perceptual difficulty chart (CR-10) (Foster et al., 2001). Additionally, a modified Physical Activity Enjoyment Scale (PACES 8) (Mullen et al., 2011) was completed by participants within 5 min of completing the SIT session, the combined total of the PACES 8 questionnaire per participant, per exercise mode were considered for statistical analysis.

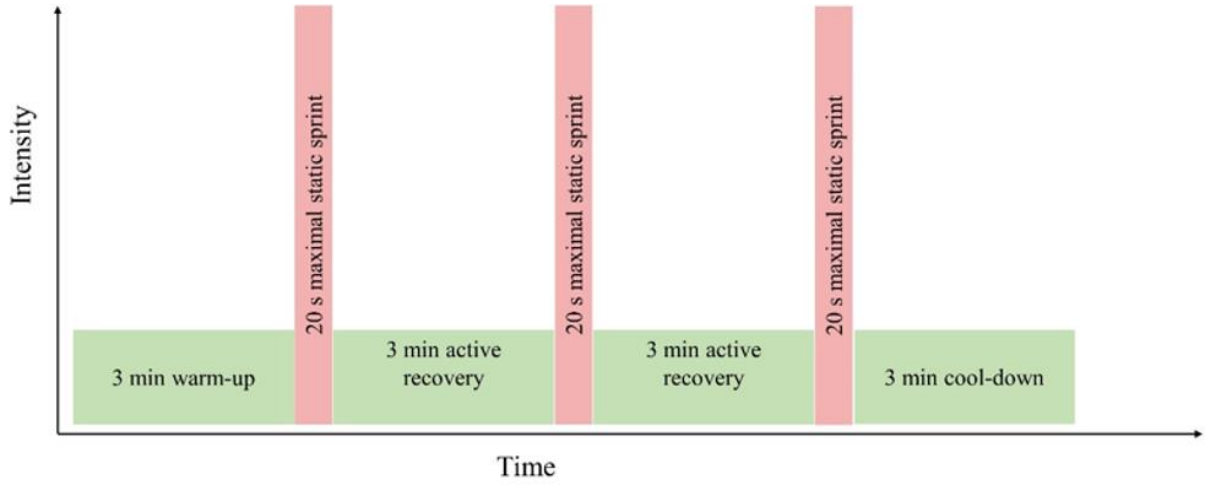


Figure 4.2.9.1 Schematic representation of sprint interval training protocol.

4.2.10 Statistical Analysis

Statistics were processed using SPSS version 23.0 (IBM, USA). A Shapiro–Wilk's test of normality and Levene's test for homogeneity of variance was conducted for all tests. Data are presented as means ± SD. For each dependent variable ($\dot{V}O_{2peak}$, HR_{peak}, RPE_{peak}, BLa_{peak}, and exercise enjoyment), a one-way repeated measures analysis of variance (ANOVA) was conducted to test for differences between exercise modes (Static Sprinting, Cycle Ergometer, Box Stepping). Alpha level was not set dichotomously as 'significant' or otherwise and is reported as exact P values as suggested by Hurlbert et al. (2019) with eta-squared (η2) used as a measure of main effect, defined as small 0.12, medium 0.20, and large 0.32 (Bryges, 2019). Bonferroni-corrected T-tests were conducted *a posteriori* to identify pairwise differences, and effect sizes were calculated using Hedges' g, defined as small (g≥0.15), medium (g≥0.40), and large (g≥0.75) (Bryges, 2019). No statistical power calculations were performed.

4.3 Results

$V\dot{O}_{2peak}$

A medium effect of exercise mode for $V\dot{O}_{2peak}$ was observed (η2=0.213, p=0.091). Post-hoc analysis revealed $V\dot{O}_{2peak}$ was smally greater for static sprinting compared to cycle ergometry (Hedges *g*=0.545, p=0.185). Static sprinting $\dot{V}O_{2peak}$ was smally greater than box stepping $\dot{V}O2_{peak}$ (Hedges g=0.278, p=0.598), whilst box stepping $\dot{V}O_{2peak}$ was smally greater than the cycle ergometer $\dot{V}O_{2peak}$ (Hedges *g*=0.23, p>0.05; Table 4.3.1).

HR_{peak}

No effect was observed for HR_{peak} between exercise modes ($\eta 2$=0.028, p=0.754). Post-hoc analysis revealed no differences between cycle ergometer to static sprinting mode (Hedges *g*=0.115, p=1.000). A smally greater HR_{peak} was observed for the static sprinting compared to the box stepping modes (Hedges *g*=0.185, p=1.000). No difference was observed between box stepping and cycle ergometry (Hedges *g*=0.053, p=1.000).

BLa_{peak}

A large effect was observed for BLa_{peak} between exercise modes ($\eta 2$ = 0.712, p<0.001). Post-hoc analysis revealed a largely greater BLa_{peak} from the cycle ergometer to static sprinting modes (Hedges *g*=0.889, p=0.030), a largely greater BLa_{peak} for static sprinting compared to the box stepping mode (Hedges *g*=1.244, p=0.009), and a largely greater BLa_{peak} for the cycle ergometer mode compared with box stepping mode (Hedges *g*=2.339, p<0.001).

Peak rating of perceived exertion (RPE_{peak})

A large effect was observed for peak RPE between exercise modes ($\eta 2$=0.390, p=0.007). Post-hoc analysis revealed a no difference between the cycle ergometer and static sprinting modes (Hedges *g*=0.043. p=1.000), a mediumly greater RPE was observed for static sprinting compared to box stepping (Hedges *g*=0.493, p=0.005), and a mediumly greater RPE was observed for the cycle ergometer compared with box stepping (Hedges *g*=0.488, p=0.043).

Physical Activity Enjoyment Scale (PACES)

A medium effect was observed for the PACES total between exercise modes ($\eta 2$=0.255, p=0.052). Post-hoc analysis revealed no difference between the cycle ergometer and static sprinting modes for the PACES total (Hedges g=0.136, p=0.915). A mediumly greater PACES total was observed for static sprinting compared with box stepping (Hedges g=0.434, p=0.261). A

mediumly greater PACES total was observed for the cycle ergometer compared with box stepping (Hedges g=0.500, p=0.225).

Table 4.3.1 Participant data for physiological and perceptual intensity, and physical activity enjoyment during different SIT exercise conditions.

	Exercise condition		
	Static sprinting (n=11)	Cycle ergometry (n=11)	Box stepping (n=11)
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	2.44 ± 0.72	2.11 ± 0.40	2.24 ± 0.66
HR_{peak} ($b \cdot min^{-1}$)	140 ± 14	138 ± 19	137 ± 17
BLa_{peak} ($mmol \cdot L^{-1}$)	6.7 ± 2.2 $^{*\ \$\$}$	8.6 ± 1.9 $^{\$\$}$	4.1 ± 1.8
RPE_{peak} (arbitrary units)	5.4 ± 2.0 $^{\$\$}$	5.5 ± 2.4 $^{\$}$	4.4 ± 1.9
PACES (arbitrary units)	44 ± 6	45 ± 8	40 ± 11

$\dot{V}O_{2peak}$, peak oxygen uptake; HR_{peak}, peak heart rate; BLa_{peak}, peak blood lactate, RPE_{peak}, peak rating of perceived exertion; PACES, Physical Activity Enjoyment Scale. Data are reported as mean ±; * results different at the $p<0.05$ level compared with cycle ergometry; ** results different at the $p<0.01$ level compared with cycle ergometry. $^{\$}$ results different at the $p<0.05$ level compared with box stepping; $^{\$}$ results different at the $p<0.01$ level compared with box stepping.

4.4 Discussion

The main findings of this study were that peak heart rate was not affected by exercise mode. However, greater peak oxygen uptake was observed during static sprinting and box stepping compared to cycle ergometry. Moreover, BLa_{peak} was greater during cycle ergometry, compared

with static sprinting, which was greater than during box stepping. Ratings of perceived exertion demonstrated that box stepping was perceived to be easier than cycle ergometry and static sprinting. PACES data suggest box stepping was less enjoyable than both the cycle ergometry and static sprinting.

4.4.1 Oxygen Uptake

Oxygen uptake is often used as a barometer to measure the intensity of exercise and is used to prescribe training intensities (Pollock et al., 1994). Therefore, it is practically significant that in the present study, there was a marked difference between static sprinting and the other modes of exercise, with the most apparent difference being observed between static sprinting and the cycle ergometer condition, with box stepping between the static sprinting and cycle ergometer conditions with trivial effects in either direction.

The present study reported a mean difference of approximately 16% in oxygen uptake between static sprinting and the cycle ergometer condition. The most significant difference between static sprinting and the cycle ergometer is likely due to cycling being a predominantly lower limb exercise, in comparison with running, which utilises a more significant effort from the upper limbs (Basset and Boulay, 2003). Although this is also true of box stepping, during laboratory protocols in the present study, many participants were more concerned with foot positioning, as opposed to muscular exertion. It is prudent to assume that with increased technical proficiency in the task, the difference between box stepping and static sprinting could be ameliorated but this would require further research to confirm. A higher oxygen uptake during exercise is associated with superior $\dot{V}O_{2max}$ adaptation and health outcomes (Rognmo et al., 2004; Tanasescu et al., 2002). Moreover, Ronnestad et al. (2020) have previously observed greater adaptations to shorter intervals of 30 s in duration when compared with 5-min intervals in effort matches protocols.

Overall, concerning aerobic fitness, static sprinting seems the most appropriate exercise mode studied to target aerobic fitness adaptations.

4.4.2 Blood Lactate

Blood lactate is an important indicator of metabolic stress, indicating a greater degree of anaerobic metabolism (Gentil et al., 2006; Goto et al., 2005; Schoenfeld, 2013). During high intensity muscular contractions, like those experienced in resistance training, SIT and HIIT, the requirement for anaerobic energy production is increased (Gibala and Little, 2020). It has been previously stated that the metabolic stress accrued from performing HIIT and SIT facilitates improved physiological health and performance (MacInnis and Gibala, 2016). This is further corroborated in the study by Fiorenza et al. (2018), which demonstrated that higher levels of metabolic stress were responsible for increased mitochondrial biogenesis, which facilitates improved physiological function.

During the present study, there was a large magnitude of difference between each exercise mode for peak blood lactate (BLa_{peak}). It is important to note that the onset of blood lactate accumulation (OBLA) is determined at 4 $mmol \cdot L^{-1}$, as such, in all exercise modes, the mean value for blood lactate was above this value. However, only in the cycle ergometer and static sprinting conditions, were the mean values observed to be consistently above OBLA, accounting for standard deviation. This suggests that the box stepping condition is likely not an efficacious mode of exercise with the SIT protocol utilised in the present study, if optimal stimulation for mitochondrial biogenesis is required (Fiorenza et al., 2018). It is noteworthy that the technical difficulties of the box stepping mode of exercise, would have likely prohibited our participants from exerting maximal effort during the present study, as it was verbalised several times during our laboratory trials.

4.4.3 Heart Rate

Heart rate is one of the primary measures of exercise intensity (Karvonen and Vuorimaa, 2012). In the present study, all the exercise modes had comparable peak heart rate values, with only trivial differences. The is despite there being significant differences in oxygen uptake and blood lactate, demonstrating the importance of not relying on a single measure of intensity to determine the efficacy and suitability of an exercise mode. This may also indicate that the factors effecting heart rate were different in between modes, with higher oxygen uptake indicative of higher cardiovascular stress, and higher blood lactate which likely induced increased heart rate via hyper stimulated chemoreceptor pathways (Ponikowski et al., 2001; Wan et al., 2020). Although the formula of 208 – age x 0.7 to ascertain a predicted maximal heart rate is not the most accurate, it is still a good approximation of maximal heart rate (Tanaka and Seals, 2001). Assuming approximate values, most of the participants analysed on the present study would have been expected to have an approximate group maximal heart rate of 160 $b.min^{-1}$, with all the exercise modes utilised in this study demonstrating that participants were demonstrably working at approximately 87% of theoretical maximal heart rate values. This is promising, as higher intensities of exercise are mechanistically linked to better cardiac adaptation or preservation (Wisloff et al., 2009).

4.4.4 Perceived Exertion, and Enjoyment

A key barrier to the adoption of higher intensity forms of aerobic and HIIT exercise has been suggested to be its purported intolerability, largely due to being perceived to be excessively difficult (Biddle and Batterham, 2015). The related afferent response to exercise has been suggested to be a key determinant of long-term exercise adherence, with positive afferent

responses being associated with chronic exercise adoption, more so than negative afferent responses (Ekkekakis, 2009).

In the present study, static sprinting and the cycle ergometer conditions corresponded with a 'hard' difficulty on the CR-10 scale. In comparison, box stepping corresponded to a 'somewhat hard' difficulty on the CR-10 scale. Previous research has demonstrated efficacy in a reduced number of sprints during sprint intervals reaching intensities of 'somewhat hard' on comparable analyses, whilst still achieving improved physiological adaptations (Vollaard and Metcalfe, 2017b). Moreover, research by Bartlett et al. (2011), demonstrated that a perceptually higher cardiorespiratory intensity of exercise is not necessarily associated with a decrease tolerability of exercise.

The results of the present study suggest the perceptual difficulty of the static sprinting and cycle ergometer conditions were harder than box stepping, yet, the enjoyment, measured using the PACES questionnaire was lower for the box stepping conditions. This demonstrates that perceived difficulty, at least up to a 'hard' difficulty as defined by the CR-10 scale is not counter to the goal of producing an enjoyable session. In our experience during the present study, on several occasions, participants found it challenging to maintain exercise momentum during sprints with the box stepping condition. This demonstrates the complexity of ascertaining what may determine the enjoyability of exercise modes. Exercising caution, it is not appropriate to extrapolate these findings during the present study to individuals who are not exercise habituated, as previous research suggests these populations may have a less positive psychological appraisal of higher intensity efforts (Biddle and Batterham, 2015). Although, as Vollaard and Metcalfe (2017b) demonstrated, it is possible to adjust perceptual difficulty by reducing interval count and duration, potentially facilitating increased enjoyability in previously sedentary individuals. It is

promising that, both static sprinting and the cycle ergometer SIT protocols were well received in terms of enjoyments whilst maintaining a high intensity of exertion both physiologically, as is indicated by the peak oxygen uptake, peak blood lactate, peak heart rate, and perceptual difficulty.

4.5 Conclusion

Physiological exercise intensity was divergent between the exercise modes, with static sprinting demonstrating the highest V̇O2, whilst cycle ergometry induced the highest blood lactate. Box stepping did not consistently achieve blood lactate concentration above the OBLA threshold. Peak heart rate was similar between all exercise conditions, generally indicating high cardiovascular stress, a prerequisite for cardiac adaptations. The static sprinting and cycle ergometer conditions were easy to perform, whilst some difficulties were experienced for the box stepping conditions. The static sprinting and cycle ergometer conditions were perceived to be harder, and simultaneously more enjoyable than the box stepping condition. Therefore, further research investigating chronic adaptations to SIT using exercise modes of static sprinting and the cycle ergometers presents a promising avenue of research.

Chapter 5: Study 3

5.1 Introduction

The previous chapter intimated SIT has a differential effect when performed in different modes in older adults, with static sprinting and cycle ergometry presenting as potentially suitable modes of SIT for stimulating cardiorespiratory and metabolic stress, which is a prerequisite for improving outcomes for both aerobic and anaerobic fitness (Hawley et al., 2014). Moreover, due to the practicality of static sprinting when compared with using cycle ergometers, with less demand for specialist equipment, it was of interest as to whether this would be an efficacious form of SIT in older adults over a training period.

As humans age, underlying biological processes culminate in the deterioration of health and function (Lopez-Otin et al., 2013). Key physical deteriorations are characterised by a loss in cardiovascular function, aerobic capacity, and muscle function, all of which decline from the third decade of life (McGregor et al., 2014; Safar, 2012). The loss in aerobic capacity is largely attributable to a decline in cardiovascular function and mitochondrial quality and quantity (Kasch et al., 1993; Yun Seo et al., 2016). Diminished cardiovascular function causes increased risk of cardiovascular disease, a major contributor to mortality (Steenman and Lande, 2017). Moreover, decreased aerobic capacity decreases physical function in performing tasks such as stair climbing, walking to the shops, etc. (Arnett et al., 2008). Losses to muscle function are generally traceable to decreased muscle mass and motor unit activation potential (Hepple, 2018; Vinciguerra et al., 2010). Consequent losses to muscle power increase risk of muscular pathologies, such as sarcopenia and dynapenia and is a major determinant of physical function in day-to-day tasks such as transitioning from sitting to standing or stepping into a bath (Mitchell et al., 2012). These deleterious changes decrease postural control of older individual which increase the risk of falling (Rath and Wade, 2017; Burns and Kakara, 2018). Therefore, exercise interventions targeting

cardiovascular function, aerobic capacity, and muscle power are of paramount importance in older populations.

An intervention which has the potential to mitigate the age-related decline in physical function is high intensity interval training (HIIT). HIIT utilises periods of high intensity exercise, interspersed by lower intensity recovery phases, and decreases time commitments to exercise by reducing the duration required to initiate adaptations (MacInnis and Gibala, 2016). The present evidence suggests repetition of the higher intensities utilised during HIIT, which are generally > 85% maximal oxygen uptake ($\dot{V}O_{2max}$), but not 'all-out' efforts, may contribute equal or greater aerobic adaptations observed during moderate intensity continuous exercise (MICT) (MacInnis and Gibala., 2016; Milanovic et al., 2015). However, HIIT has attracted criticism due to its high perceived intensity, which critics suggest may be a key determinant in preventing its wider adoption (Biddle and Batterham, 2015). Interestingly, however, a derivative of HIIT, sprint interval training (SIT), has demonstrated the potential to introduce an alternative format of training whilst still promoting increased physiological function (Gist et al., 2014). SIT is characterised by short sprints ranging from 10-30 seconds at an 'all-out' intensity, which are interspersed by lower intensity phases of recovery (MacInnis and Gibala, 2016). Moreover, SIT, compared with HIIT, reduces time commitments further, simultaneously reducing perceived exertion, whilst providing comparable adaptations that are observed in both MICT and HIIT interventions (Milanovic et al., 2015). Although, the mechanism for improving physiological function differ between MICT, HIIT, and SIT, with increased emphasis on metabolic stress with HIIT and SIT as effective stimulants for physiological adaptation (Fiorenza et al., 2018). Moreover, the use of 'all-out' intensities used in SIT reduces barriers to adoption, with easier prescription, removing the need to monitor intensity, and the need for specialised equipment, such as power meters, heart rate monitors, or gas analysers (Buchheit and Laursen, 2013a).

In addition to cardiovascular adaptations, SIT improves muscle power in young cohorts (Farzad et al., 2011; Kim et al., 2011). Additionally, one study in older adults utilising repeated short 'all-out' sprints has observed improved cardiovascular function, and increased power (Adamson et al., 2018). Taken together, the primary aim of the present study was to investigate effects of an accessible static sprinting SIT programme in a group of physically active older adults on: (1) muscle power (determined by a Herbert 6s test and counter-movement jump [CMJ]) (2) aerobic fitness (determined using a standard ramped $\dot{V}O_{2max}$ incremental protocol) (3) cardiovascular function (measured by blood pressure, resting heart rate [HR], HR_{peak}, mean arterial pressure, and pulse pressure). A secondary aim was to investigate the effects of SIT on postural control, measured via a standing postural sway test. *A priori*, we hypothesised muscle power, aerobic fitness, cardiovascular function, and postural control would improve following SIT.

5.2 Methods

5.2.1 Participants

This study was carried out in accordance with the Declaration of Helsinki and approved by the University of Cumbria Research Ethics Committee (Reference code: 16/74). Written informed consent was obtained from all participants prior to study commencement. A Physical Activity Readiness Questionnaire (PAR-Q) and American College of Sports Medicine (ACSM) pre-exercise participation screening was completed (Riebe et al., 2015). Participants were 13 older participants (10M/3F, mean age of 68.2±7.8 years, height of 171.7±9.6 cm). Participants were habitually physically active, exercising at least twice a week, totaling at least 150 minutes of moderate intensity exercise per week, without exercise contraindicating disease or injury.

Abstention from alcohol, caffeine, was required for 24 hours prior to testing sessions, with an extended exercise abstention of 48 hours prior to testing.

5.2.2 Experimental Design

The study was a randomised trial with a time delayed phase. On day 1, following consent and screening procedures, participants completed a familiarisation session. On day 5, participants completed the phase A test battery. Day 5 to 33 incorporated as a control phase, where participants continued habitual physical activity only. On day 35, participants completed the phase B test battery. Between day 40 to 96, participants underwent SIT, whilst maintaining habitual physical activity. On day 101, participants completed the phase C test battery.

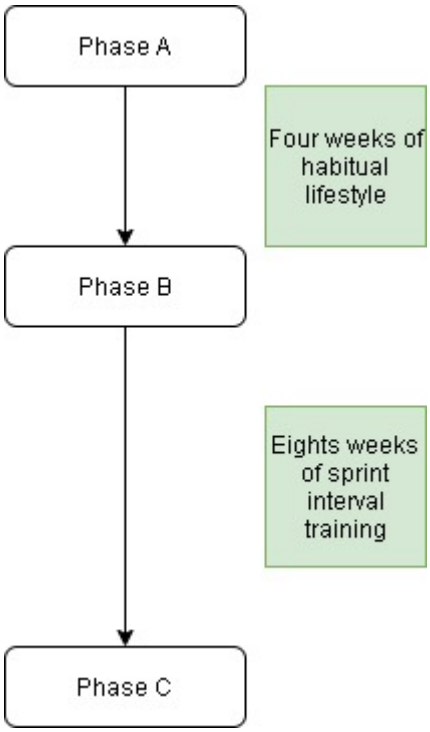


Figure 5.2.2.1 Schematic of study timeline as phase A, B, and C.

5.2.3 Familiarisation

Whilst wearing the heart rate monitor and rubber face mask, participants performed a warm-up on a cycle ergometer (Wattbike Pro, Wattbike Ltd, UK), consisting of 6 minutes of cycling at 70 W, interspersed evenly with three ~2 s maximal sprints with an air brake resistance of 8 and a magnetic resistance of 1. Following warm-up, participants performed a Herbert 6s test, as described below. Subsequently, participants were instructed how to perform a countermovement jump, with their hands on their hips until technical proficiency and consistency was demonstrated, which was judged by the lead researcher.

5.3 Testing Protocol

Participants were fasted from 22:00 h the previous night and attended the exercise physiology laboratory between 08:00-11:00 h. On arrival, participants were asked verbally to confirm that they had adhered to the prerequisite controls stated previously to increase internal validity. Subsequently, participants were tested for the following parameters, in the order listed: height, bod mass, body mass index (BMI), blood pressure, resting heart rate, postural sway, peak power output (PPO), countermovement jump performance, and $\dot{V}O_{2max}$. These tests were conducted at phase A, B, and C in identical order, with participants allocated to similar testing times to control for diurnal variation (Hayes et al., 2010).

5.3.1 Height, Body Mass, and Body Mass Index (BMI)

Participants removed footwear and emptied pockets. Participants then stepped on to a measuring station (Seca, 286), to measure height (cm), mass (kg), and body mass index (BMI) accurate to 1 decimal place.

5.3.2 Blood Pressure and Resting Heart Rate

Participants were seated for a period of 5-minutes before the test. An occlusion cuff was attached on the left arm, which was rested on an arm rest at chest level. The blood pressure monitor (Omron Corporation, Omron HEM-7361T-ESL, Japan) was then activated to measure systolic and diastolic blood pressure (mmHg) and resting heart rate ($b.min^{-1}$), three times, with 1 min between each measure, the mean of the three measurements was recorded. Mean arterial pressure was calculated using the formula:

$$MAP = DP + \frac{1}{3}(SP - DP)$$

Whereby: MAP = mean arterial pressure, DP = diastolic pressure, SP = systolic pressure

5.3.3 Postural Sway

Participants were fitted with gyroscopic sensors (OPAL, APDM, USA), at the ankles and the trunk, a sway detection software (Mobility Lab, APDM, USA) was set to measure movement over 30 s. Participants were then required to stand 2 m away from a wall, with a visual focus marked 'X', set approximately at eye level for each participant. Participants stood with their hands on their hips, feet shoulder width apart, on a firm surface with their eyes open for a period of 30 s. Data extracted was the root mean square of the sway (RMS sway acceleration $m.\ s^{-2}$).

5.3.4 Power Testing

A Herbert 6 s test was conducted as previously described (Herbert et al., 2015a). Subsequently, participants stood on a force platform (AMTI Accupower Portable Platform, AMTI, USA), set to sample at 400 Hz for a period of 10 s using the force platform software (Accupower Software 2.0,

AMTI, USA). Once participants weight was measured (N), participants performed three unrecorded practice counter-movement jumps (CMJ) interspersed by 10 s of rest. Following 2 min' rest, participants performed three maximal effort CMJs interspersed by 1 min rest intervals. All CMJs were performed with the participants' hands on their hips, to avoid interference from arm sway. Extracted data was peak power output, and the greatest jump height for which the highest recorded values of the three jumps were analysed.

5.3.5 $\dot{V}O_{2max}$ Test

A chest strapped heart rate monitor was attached with heart rate measured continuously throughout the test (Polar F1, Polar, Finland). The cycle ergometer (Wattbike, Wattbike Pro, UK) was adjusted to manufacturer's requirements. Participants mounted the cycle ergometer, and a rubber face mask was fitted (Hans Rudolph Inc, USA), which was attached to a breath-by-breath gas analysis system (Cortex Metamax 3B, Cortex Biophysik, Germany). $\dot{V}O_2$ and VCO_2 were recorded continuously throughout the test. Participants completed a 3-minute warm-up at an intensity equivalent to ~10% of their peak power output, obtained during the Herbert 6 s test. During the last minute of the warm-up, participants' RPE was recorded using a CR-10 scale (Foster et al., 2001). Subsequently, participants cycled at an increasing intensity with 25 W increments each minute until they reached volitional exhaustion, with RPE recorded immediately prior to each incremental increase. Immediately following volitional exhaustion, participants had their index finger cleaned using a disinfectant wipe, and then a lancet was used to lacerate the fingertip to obtain a blood sample for the measuring strip inside a blood lactate analyser (Lactate Pro 2, Arkray, Japan). The highest observed values for heart rate, RPE, and blood lactate were recorded for analysis. Moreover, power output at test termination was recorded. For reliable extraction of $\dot{V}O_{2max}$ and anaerobic threshold (AT), a 10-breath moving average was used to determine $\dot{V}O_{2max}$ and the AT. AT was digitally identified as a respiratory exchange ratio of 1.0.

O_2 pulse was calculated was calculated as absolute $\dot{V}O_{2max}$ divided by heart rate at the time of $\dot{V}O_{2max}$.

5.3.6 Sprint Interval Training

Participants stood in a 1 m^2 area and warmed up for 3 minutes at a self-paced intensity by performing a static run. Participants then performed three 20 second static sprints at an 'all-out' intensity, interspersed by 3-minute self-paced recovery phases. Following the final sprint, a 3-minute self-paced static running cool down was performed. During all sprints, participants were instructed to lift their feet to approximately knee height, with loud verbal encouragement until the end of the sprint. Below is a schematic representation of the SIT intervention (**Figure 5.3.6**).

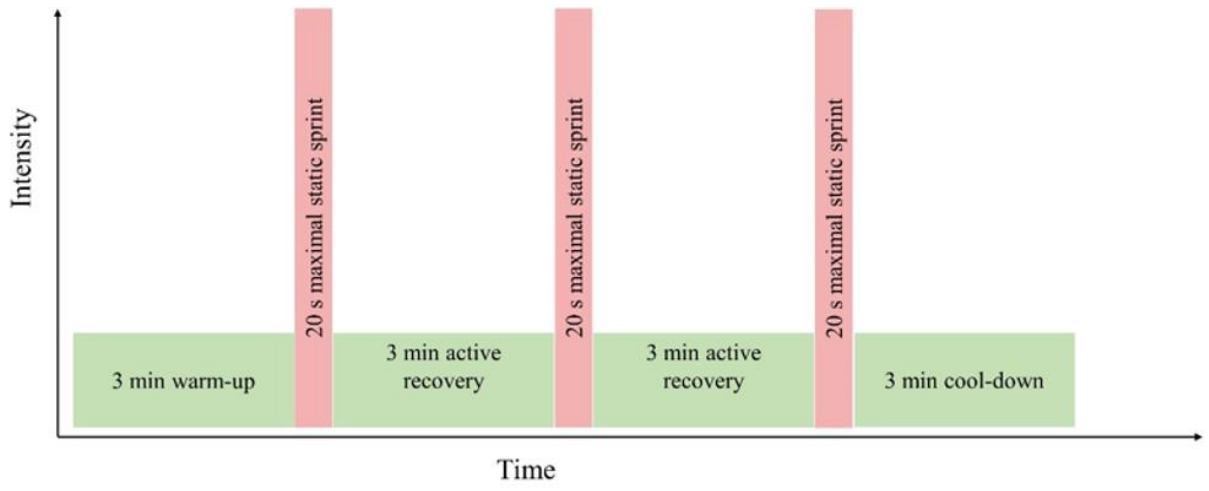


Figure 5.3.6.1 Schematic representation of sprint interval training protocol

5.4 Statistical Methods

Statistics were processed using SPSS version 23.0 (IBM). Following a Shapiro–Wilk's test of normality and Levene's test for homogeneity of variance, a one-way repeated measures analysis of variance

(ANOVA) was conducted for all dependent variables between test phases (A, B, and C). Alpha level was not set dichotomously as 'significant' or otherwise and is reported as exact P values as suggested by Hurlbert et al. (2019) with eta-squared (η2) used as a measure of main effect, defined as small 0.12, medium 0.20, and large 0.32 (Bryges, 2019). Bonferroni-corrected T-tests were conducted *a posteriori* to identify pairwise differences, and effect sizes were calculated using Hedges' g, defined as small (g≥0.15), medium (g≥0.40), and large (g≥0.75) (Bryges, 2019). No statistical power calculations were performed.

5.5 Results

Anthropometry

Body mass index (BMI)

There was a small effect of time on BMI (p=0.210, n^2=0.122). Post-hoc analysis revealed no differences between phase A and B (p=0.510, g=0.069), B and C (p=0.551, g=0.102), and A and C (p=1.000, g=0.032) (**Table 5.5.1**).

Hemodynamics

Systolic blood pressure

There was a small effect of time on systolic blood pressure (p=0.111, n^2=0.167). Post-hoc analysis revealed systolic blood pressure was smally greater at phase A compared with phase B (p=0.038, g=0.277), and smally greater at phase B compared with phase C (p=0.525, g=0.176), and mediumly greater at phase A compared with phase C (p=0.068, g=0.455).

Diastolic blood pressure

There was a medium effect of time on diastolic blood pressure (p=0.027, n^2=0.260). Post-hoc analysis revealed diastolic blood pressure was smally greater at phase A compared with phase B (p=0.034, g=0.305), and smally greater at phase B compared with phase (p=0.248, g=0.194), and mediumly greater at phase A compared with phase C (p=0.001, g=0.571).

Mean arterial pressure

There was a large effect of time on mean arterial pressure (p=0.027, n^2=0.260). Post-hoc analysis revealed mean arterial pressure was smally greater at phase A than at phase B (p=0.015, g=0.369), and smally greater at phase B than at phase C (p=1.000., g=0.194), and mediumly greater at phase A than at phase C (p=0.109, g=0.571).

Resting heart rate

There was no effect of time on resting heart rate (p=0.578, n^2=0.045). Post-hoc analysis revealed no change from A to B (p=0.952, g=0.107), B to C (p=1.000, g=0.121), or from A to C (p=1.000, g=0.000).

HR_{peak}

There was a medium effect of time on HR_{peak} (p=0.032, n^2=0.250). Post-hoc analysis revealed no change from phase A to phase B (p=1.000, g=0.000), and was smally greater at phase C than at phase B (p=0.010, g=0.310), and smally greater at phase C than at phase A (p=0.109, g=0.310).

Balance

Postural sway

There was no effect of time on postural sway (p=0.258, n^2=0.107). Post-hoc analysis revealed postural sway was smally greater at phase B than at phase A (p=1.000, g=0.161), and smally

greater at phase C than at phase B (p=0.445, g=0.201), and smally greater at phase C than at phase A (p=0.419, g=0.390).

Muscle power

Hebert 6 s PPO test

There was a large effect of time on muscle power measured by the Herbert 6s PPO test (p=0.018, n^2=0.517). Post-hoc analysis revealed no differences from A to B (p=1.000, g=0.040), a smally greater PPO at phase C than at phase B (p=0.035, g=0.200), and a smally greater PPO at phase C than at phase A (p=0.012, g=0.238).

Countermovement jump power

There was a large effect of time on countermovement jump power (p=0.008, n^2=0.332). Post-hoc analysis revealed no change from A to B (p=1.000, g=0.027), a smally greater jump power at phase C than at phase B (p=0.020, g=0.319), and a smally greater jump power at phase C than at phase A (p=0.027, g=0.376).

Countermovement jump height

There was a large effect of time on countermovement jump height (p=0.004, n^2=0.370). Post-hoc analysis revealed no change from A to B (p=1.000, g=0.079), A mediumly greater jump power at phase B than at phase C (p=0.003, g=0.424), and a smally greater jump power at phase C than at phase A (p=0.016, g=0.371).

Aerobic performance

$\dot{V}O_{2max}$

There was a small effect of time on $\dot{V}O_{2max}$ (p=0.017, n^2=0.137). Post-hoc analysis revealed no change from A to B (p=1.000, g=0.133), a smally greater $\dot{V}O_{2max}$ at phase C than at phase B (p=0.194, g=0.303), and smally greater $\dot{V}O_{2max}$ at phase C than at phase A (p=0.970, g=0.162).

O_2 pulse

There was no effect of time on O_2 pulse (p=0.289, n^2=0.009). Post-hoc analysis revealed no change from A to B (p=0.821, g=0.149), a smally greater O_2 pulse at phase C than at phase B (p=0.329, g=0.233), and no change from A to C (p=1.000, g=0.053).

Anaerobic threshold as a percentage of $\dot{V}O_{2max}$

There was a medium effect of time on the anaerobic threshold as a percentage of $\dot{V}O_{2max}$ (AT % @ $\dot{V}O_{2max}$) (p=0.035, n^2=0.243). Post-hoc analysis revealed a smally greater AT % @ $\dot{V}O_{2max}$ at phase B than at phase A (p=0.915, g=0.180), a medium greater AT % @ $\dot{V}O_{2max}$ at phase C than at phase B (p=0.285, g=0.442), and mediumly greater AT % @ $\dot{V}O_{2max}$ at phase C than at phase A (p=0.107, g=0.695).

Power at $\dot{V}O_{2max}$

There was a medium effect of time on power at $\dot{V}O_{2max}$ (p=0.010, n^2=0.292). Post-hoc analysis revealed no change from A to B (p=0.677, g=0.111), a smally greater maximum power at $\dot{V}O_{2max}$ at phase C than at phase B (p=0.153, g=0.166), and a smally greater $\dot{V}O_{2max}$ at phase C than at phase A (p=0.065, g=0.264).

Table 5.5.1 Effects of SIT in older adults on anthropometry, hemodynamics, balance, muscle power, aerobic and anaerobic performance for phase A, B, and C.

	Study Phase		
	A (Control)	B (Pre-intervention)	C (Post-intervention)
Anthropometry			
Height (cm)	171.6 ± 10	-	-
Weight (kg)	69.9 ± 10	69.2 ± 9	70.1 ± 10
BMI ($kg \cdot m^{-2}$)	23.7 ± 3.0	23.5 ± 2.6	23.8 ± 3.1
Hemodynamics			
Systolic BP (mmHg)	137±18	132±17*	129±16
Diastolic BP (mmHg)	80±10	77±9*	76±9
MAP (mmHg)	99±11	95±10*	93±10
RHR ($b.min^{-1}$)	56±10	57±8	56±8
HR_{peak} ($b.min^{-1}$)	151±12	151±12[a]	155±13
Balance			
Postural Sway ($mm.s^2$)	56.3±5.9	59.3±2.0	63.3±8.5
Muscle power			
Herbert 6s PPO (W)	599±167	606±169 [a]	640±167
CMJ ($W.kg^{-1}$)	29±4	29±5 [a]	31±6
CMJ (cm)	19.6±4.6	19.2±5.2 [b]	21.5±5.3
Aerobic performance			
$\dot{V}O_{2max}$ ($ml.kg.min^{-1}$)	37.41±8.22	36.34±7.3	38.80±8.40
O_2 pulse ($ml.b.min^{-1}$)	17.3±4.2	16.7±3.6	17.5±3.0
AT % of $\dot{V}O_{2max\ x}$	78.7±9	80.4±9.3	84.1±6.7
Power at $\dot{V}O_{2max}$ (W)	223±55	229±50	238±55

BMI, body mass index; BP, blood pressure; MAP, mean arterial pressure; RHR, resting heart rate; HR_{peak}, peak heart rate; PPO, peak power output; CMJ, countermovement jump; $\dot{V}O_{2max}$,

maximal aerobic capacity; O_2, oxygen; AT, anaerobic threshold. *p<0.05 phase B to C; [a]p<0.05 phase A to B; [b]p<0.01 phase C to A.

BMI, body mass index; BP, blood pressure; MAP, mean arterial pressure; RHR, resting heart rate; HR_{peak}, peak heart rate; PPO, peak power output; CMJ, countermovement jump; $\dot{V}O_{2max}$, maximal aerobic capacity; O_2, oxygen; AT, anaerobic threshold; Max, maximum. *p<0.05 phase B to C; [a]p<0.05 phase A to B; [b]p<0.01 phase C to A.

5.6 Discussion

The main finding of this study was that a novel SIT protocol intervention produced increases in muscle power, hemodynamic function, and aerobic capacity in already physically active older adults. However, some increase in postural sway was observed.

5.6.1 Hemodynamics

Cardiac function is a leading target for exercise interventions for several reasons (Anderson et al., 2016; Babette et al., 1999; and Fukuta et al., 2019). Firstly, pathological developments to heart function are the leading causes of death in developed nations (Lozano et al., 2012). Secondly, optimising athletic performance, and more specifically, aerobic capacity, is highly dependent on cardiac function (Lundby et al., 2019). It is proposed that a decrease to maximal heart rate is a major contributor to age associated declines in aerobic capacity (Pina et al., 2003), despite better maintenance of cardiac dilation and stroke volume (Rodeheffer et al., 1984). Ageing precipitates a decline in maximal heart rate that is independent of all forms of exercise training, although moderate to high intensity exercise that places a hormetic stress on cardiorespiratory function can

attenuate this decline (Kasch et al., 1999). It is proposed that a decreased maximal heart rate is attributable to diminished sinoatrial node function (Larson et al., 2013). Moreover, cardiorespiratory fitness is associated with higher maximal heart rate values (Ozemek, et al., 2015). This is logical, as cardiac output is derived from stroke volume multiplied by heart rate (Lundby et al., 2019). For reference, research by Ozemek et al., (2015), observed a difference of approximately 5.2% in maximal heart rate between low and medium fitness individuals. In the present study, the increase in maximal heart rate following 8 weeks' SIT is ~2.6%. Christou and Seals (2008) reported decreased maximal heart rate is primarily due to detriments to sinoatrial node innervation mechanisms. It would be reasonable to speculate if increased maximal heart rate following SIT may be due to restoration of sinoatrial node mechanisms, as maximal heart rate increases following aerobically stressful exercise training are unlikely to be related to increased cardiac output, as this is mechanistically independent of maximal heart rate (Lundby et al., 2019). Furthermore, the present study did not observe a change to resting heart rate, which is generally associated with changes to stroke volume (Koskela et al., 2013). However, the complexity of the sinoatrial node, cardiac morphology, and its biological effectors, reviewed in depth by MacDonald et al. (2020), does not justify meaningful speculation on the mechanism of change, especially when combined with the small sample size in the present study. However, further mechanistic investigation of the effects of SIT on maximal heart rate are justified.

Increased blood pressure above normal values, termed hypertension, is implicated in pathological developments in human physiology, predominantly due cardiovascular disease (Wong et al., 2001). Therefore, improving (reducing) blood pressure is of interest in exercise research, with evidence suggesting exercise is a therapeutic measure in managing blood pressure (Pescatello et al., 2004: Sharman et al., 2019). In the present study, blood pressure measured at phase A was higher than phase B and phase C. This observation is unexpected given that participants

maintained habitual physical activity between phases A and B. However, one explanation may be the ‘white coat effect’ when measuring blood pressure in test settings (Nawata and Kimura et al., 2017; Feitosa et al., 2019). This was despite an attempt to familiarise participants to blood pressure measurements, as part of the pre-participation screening. To minimise this ‘white coat effect’ blood pressure measurements may require use of remote measuring techniques isolated from the researcher and laboratory setting.

It is noteworthy that there were small differences between phase A to B and medium effects between phases A to C which suggests SIT robustly lowered systolic, diastolic, and mean arterial pressure, over and above reduction of the white coat effect. SIT reduced overall blood pressure by approximately 5-6% for systolic, diastolic, and mean arterial pressure values. Furthermore, these findings are corroborated by Bahmanbeglou et al. (2019), who demonstrated similar reductions to blood pressure following two different HIIT protocols. More importantly, group means for systolic and diastolic blood pressure values were within the values determined to be stage one hypertension as defined by Muntner et al. (2019) at phase A, and were reduced to the lower risk, ‘elevated’ level by phase C. This represents an overall risk reduction in risk for cardiovascular disease, coronary heart disease, and stroke of 18%, 18%, and 20% respectively (Jones et al., 2021).

5.6.2 Muscle Power

Previous research has demonstrated that healthy muscle function is a requirement in maintaining overall physical function (Clark and Manini, 2010). Although strength is an important determinant of physical function, a previous review by Byrne and colleagues (2016) highlights the importance of muscle power for performing functional tasks. Emerging research suggests SIT may increase muscle power in young cohorts (Farzad et al., 2011; Kim et al., 2011; MacDougall,

1998). In older untrained individuals, Adamson et al. (2018) utilised extremely short duration sprint intervals (6 s) interspersed by 60 s rest performed twice a week over 10 weeks. Adamson et al. (2018) observed an increase in stair-climbing power of ~13%. In comparison, the present study observed an increase in power of approximately ~6-10% (dependent upon measurement method considered). HIIT interventions of a lower weekly frequency have observed increases of ~17% in previously sedentary adults PPO (Sculthorpe et al., 2017), and 8% in master athletes (Herbert et al., 2017). Thus, findings presented here are similar in magnitude to those reported in trained older individuals, and participants within the present study were older than those in the Herbert et al. (2017) study, which is encouraging, as the likelihood of muscle weakness increases with age (Byrne et al., 2016).

5.6.3 Aerobic Capacity

Aerobic capacity as a measure of cardiorespiratory fitness is strongly linked both epidemiologically and mechanistically to prevalence and mortality of cardiovascular disease, a leading cause of death in developed nations (Ozemek et al., 2018). A meta-analysis by Sloth et al. (2013) investigating the effects of SIT on $\dot{V}O_{2max}$ reported an increase to aerobic capacity following HIIT. Furthermore, Sloth et al. (2013) postulated the increase in aerobic capacity was likely due to peripheral muscular adaptations, such as capillarisation. Moreover, HIIT in older adults has yielded an increased aerobic capacity in previous studies (Grace et al., 2017; Hwang et al., 2016; Kim et al., 2017; Knowles et al., 2015; Lepretre et al., 2009; Molmen et al., 2012; Storen et al., 2017; Sogaard et al., 2017; Wyckelsma et al., 2017). The findings of the present study corroborate previous findings with an approximate increase of 7% to $\dot{V}O_{2max}$. Previous research has demonstrated that a >6% change to aerobic capacity over a 3-month period leads to decrease in all-cause mortality in persons with heart disease. Moreover, the 2.4 $ml.kg.min^{-1}$ increase to aerobic capacity observed from phase A to C shifted the group mean from the 90^{th} to

the 95th percentile of age-adjusted reference figures for aerobic capacity in two distinct populations (Kaminsky et al., 2015; Rapp et al., 2018).

5.6.4 Postural Stability

The increase in RMS sway acceleration observed in the present study, a measure of postural stability, is unexpected and somewhat unexplainable, as we had hypothesised an improvement in postural stability through neuromuscular adaptations of the lower limbs. The location of the research study (Lancaster, UK) means serum Vitamin D likely declined in our participants due to time of year (November 2019 to March 2020) (Calame et al., 2020). Importantly, Boersma et al. (2012), demonstrated increased postural sway associated with lowered Vitamin D status. However, the magnitude of the findings was small, and unlikely to be clinically meaningful, as previous research has demonstrated risks are associated with relatively high path lengths of 400 mm and 920 mm, corresponding to an increased fall risk of 75% to 200% respectively (Johansson et al., 2017). In this context, a post hoc determination of the critical difference (a method for combining analytical and biological variation to determine biologically relevant thresholds) of RMS sway acceleration resulted in a threshold of 62%, and changes reported in this study were 11% from phase A to C. Thus, the small effects observed herein were likely artefactual, and a result of analytical or biological variation. A previous meta-analysis measuring the effect of exercise interventions on postural control (measured by center of pressure) reported no benefit of either strength, or multi-component exercises inclusive of balance, endurance, and strength components (Low et al., 2017). Conversely, specific balance training exerted a positive effect on postural control. This demonstrates that balance adaptations in older adults differ according to exercise prescription. The findings by Low et al. (2017), when combined with the current findings suggest that SIT may not be suitable stimulus for improving postural sway, and therefore,

recommendations provided by Low et al. (2017), which suggest that only balance training can improve postural are corroborated by the findings in this study.

From these findings, SIT has the potential to be impactful in improving hemodynamic, cardiac, muscle power, and aerobic performance in older persons. We were able to detect changes of small to medium magnitude to in an active group, who likely have less adaptive potential than a comparable group of lower fitness. However, the issue of attraction to an inactive population needs further investigation as previous research has emphasised (Biddle and Batterham, 2015). As in our recruitment, prospective participants and participating participants were all previously active. There is some comparable research by Adamson et al. (2014, 2018) with repeated sprint training demonstrates efficacy in a lesser trained older adult population over 10 weeks, it is unlikely to fulfill the intensity requirements for continued adaptation over a significantly longer time (MacInnis and Gibala, 2016; Fiorenza et al., 2018). However, it would be prudent to investigate a progressive intensity SIT intervention that utilises extremely short 6s sprints as used by Adamson et al. (2014, 2018) in the initial stages of intervention, and potentially progressing to 15 s sprints as proposed by Vollaard and Metcalfe (2017a). Moreover, the ease of prescription with 'all-out' intervals is a key practical consideration with SIT over HIIT.

5.7 Limitations

The present findings are limited by several factors. The small sample size of the present study invites caution to the findings and interpretations (Faber and Fonseca, 2014). However, as no previous work with SIT in older adults has been conducted, an *a priori* sample size calculation was problematic given the unknown change in means. Moreover, this work was exploratory and therefore sample size calculations may not be appropriate given interpretation was magnitude

based. However, larger confirmatory studies are required to confirm findings of the present study. Participants of the present study were previously active, and therefore findings cannot be extrapolated to sedentary populations, though it is likely to be of higher magnitude (Grace et al., 2017; Sculthorpe et al., 2017). Controlling for the impact of vitamin D should be standard in future research as it is relatively easy to implement and the absence of it may have a significant impact on outcomes (Christakos et al., 2015).

5.8 Conclusion

In conclusion, the present study investigating SIT in older adults observes increases muscle power, hemodynamic function, and aerobic capacity in already physically active older adults. Therefore, SIT in older adults may present as an accessible, easy to perform alternative to seldom followed guidelines of more time intensive aerobic training protocols. However, the sample size and study controls were limited, and vitamin D status was not controlled for, which future research should correct for.

Chapter 6: General Discussion

6.1 Initial Aims of the Thesis

The initial aims of this thesis were to investigate the effects of HIIT and SIT in older adults utilising a systematic review meta-analysis of the literature as identified by the aims and hypotheses stated earlier in the thesis, which will be used as a reference to conclude the findings of this thesis against the broader literature. The systematic review and meta-analysis did not identify any SIT interventions in older adults. Therefore, this necessitated an investigation concerning SIT in older adults. As such, three primary studies with distinct aims were devised. Study 1 had the aim of assessing peak power recovery following SIT at 3 days and 5 days of rest in physically active older adults, as power output is of key importance to physical functioning in older adults (Byrne et al., 2016). Study 2 followed up with the aim of determining the difference in the effects on physiological, psychological, and perceptive responses of different SIT modes, comparing static sprinting, cycle ergometry, and box stepping in physically active older adults. Findings of study 2 identified static sprinting and cycle ergometry as the most physiologically intense, so due to no ecological validity of statis sprinting, the efficacy of a static sprinting SIT intervention as tested in study 3. Study 3 investigated the physiological effects of 8 weeks of static sprinting SIT in physically active older adults. Therefore, the original contributions of this thesis include: 1) Meta-analysing HIIT interventions in older adults on $\dot{V}O_{2max}$, muscle strength, muscle mass, and body fat for the first time, 2) Assessing the recovery at 3 and 5 days of rest following SIT in physically active older adults, 3) Comparing the physiological, psychological, and perceptive responses to a SIT protocol across three distinct modes of exercise in physically active older adults, and 4) Observing the effects of 8 weeks of static sprinting SIT in physically active older adults.

6.2 Meta-Analysis Findings

Aerobic capacity is a crucial predictor of all-cause mortality in older adults (Mandsager et al., 2018), and the findings of this systematic review and meta-analysis strongly support hypothesis H5, with the overall standard difference in means (SDM) for aerobic capacity following HIIT being 0.73 (p=0.001). Several studies reported significant improvements in aerobic capacity (V̇O2max or VO2peak) following HIIT interventions (Boukabous et al., 2019; Bruseghini et al., 2015; Bruseghini et al., 2019; Grace et al., 2018; Hurst et al., 2019; Hwang et al., 2016; Kim et al., 2017; Knowles et al., 2015; Lepretre et al., 2009; Molmen et al., 2012; Søgaard et al., 2017; Søgaard et al., 2019; Støren et al., 2017; Wyckelsma et al., 2017). Molmen et al. (2012) conducted a study on older adults (mean age: 72 years) with varying training status, including sedentary and physically active individuals. The intervention consisted of treadmill running with 4 x 4-minute intervals at 87% V̇O2max interspersed by active recovery, performed three times a week for 12 weeks. The study reported the highest improvement in aerobic capacity of 15.6% among the studies included in the meta-analysis. In contrast, Knowles et al. (2015) reported the lowest improvement with 3.9% for lifetime exercising older men (mean age: 62 years) following a 6-week cycling HIIT intervention (6 x 30-second intervals at 40% of absolute peak power output interspersed by 3 minutes of active recovery), which generally corresponds to above 100% of PPO relative to $\dot{V}O_{2max}$. It is likely that these differences can be explained by the initial level of the participants in the respective studies, alongside the longer duration of the intervention for Molmen et al. (2012). Encouragingly, despite a 10-year mean age gap between the Knowles et al. (2015) study, and Molmen et al. (2012) study, improved aerobic fitness was achieved. Moreover, Lepretre et al. (2009) reported a 14.7% increase in aerobic capacity for older men and a 14.5% increase for older women following a 9-week HIIT intervention consisting of 6 x 1-minute intervals at ventilatory threshold two (VT2). VT2 typically corresponds to approximately 80-90% of maximal heart rate (HRmax) and 60-85% of peak power output (PPO) relative to V̇O2max

(Bentley et al., 2007). This suggests that despite the lower interval volume of just 6 minutes, compared against 16-minutes with the Molmen et al. (2012) study, substantial improvement to aerobic fitness can be obtained.

Milanović et al. (2015) conducted a systematic review and meta-analysis on the effects of HIIT on cardiorespiratory fitness in healthy, physically inactive, and predominantly young adults. The authors found that HIIT led to significant improvements in $\dot{V}O_{2max}$, with an overall effect size of 0.92, demonstrating the efficacy of HIIT in enhancing aerobic capacity in this population. In addition to older adults, HIIT interventions have shown to be effective in improving aerobic capacity in other populations. For example, young adults participating in a 7-week HIIT program experienced significant improvements in $\dot{V}O_{2max}$ compared to a traditional endurance training group (Helgerud et al., 2007). Similarly, a study by Wisløff et al. (2007) demonstrated that patients with coronary artery disease who underwent 12-week HIIT intervention experienced significant improvements in aerobic capacity, as well as enhanced endothelial function and reduced symptoms of angina.

In summary, this systematic review and meta-analysis provide substantial evidence supporting the effectiveness of HIIT interventions in improving aerobic capacity among older adults and various other populations. The included studies, such as those by Molmen et al. (2012) and Knowles et al. (2015), highlight the adaptability of HIIT protocols to suit participants with different ages, training statuses, and physiological conditions. Further research is needed to determine the optimal HIIT protocols and compare their effectiveness with other training modalities to maximise health outcomes in various populations, considering factors such as age, training status, and health conditions.

In expanding on the findings of Hurst et al. (2019) and Bruseghini et al. (2015; 2019), several other studies corroborate the relationship between High-Intensity Interval Training (HIIT) and improved muscle power and strength in older adults. Boukabous et al. (2019) observed in their study on older women (mean age: 66 years) that an 8-week program of treadmill exercise, consisting of 6 x 1-minute intervals at 90% HR reserve conducted thrice a week, led to a 13% increase in muscle strength. Similarly, the 2015 study by Bruseghini et al. on healthy elderly subjects (mean age: 68 years) showed that an 8-week aerobic interval training program comprising 7 x 2-minute intervals at 85-95% V̇O2max interspersed by 2 minutes of recovery at 40% V̇O2max, conducted thrice a week, led to a 13.7% increase in muscle strength in the leg extensors. In their 2019 study on healthy males (mean age: 68 years), the same program led to a 12.9% increase in muscle strength in the knee extensors. Furthermore, the Grace et al. (2018) study involving sedentary older men (mean age: 62 years) and lifetime exercising older men (mean age: 61 years) demonstrated the benefits of a 6-week cycling exercise program, comprising 6 x 30-second intervals at 50% peak power output with 3 minutes of recovery at low resistance conducted every 5 days. The program led to an 11.9% and 7.8% increase in $\dot{V}O_{2max}$ for sedentary and lifetime exercising men, respectively.

The Herbert et al. (2017) study on male masters athletes (mean age: 61 years) saw an 8.3% increase in muscle power after a 6-week cycling exercise program, with 6 x 30-second intervals at 40% peak power output interspersed by 3 minutes of active recovery. In their 2016 study, Herbert et al. found a 3.0% increase in fat-free mass (FFM) post-HIIT in sedentary aging men (mean age: 62 years), and a 4.0% increase in masters athletes (mean age: 60 years) following the same regimen. Hurst et al. (2019) reported in their study on older adults (mean age: 62 years) that a 12-week program of assorted multi and single joint exercises, including 12-20 minute sessions with 3-minute passive recovery between intervals at a mean intensity of 82% HR_{max} and peak intensity

of 89% HR_{max} performed twice a week, led to an approximately 10.5% increase in muscle power and a 4.5% increase in muscle strength. These studies, along with the findings from Hwang et al. (2016), Kim et al. (2017), Knowles et al. (2015), Lepretre et al. (2009), Molmen et al. (2012), Sculthorpe et al. (2017), Søgaard et al. (2017; 2019), Støren et al. (2017), and Wyckelsma et al. (2017), provide robust evidence in favour of the hypotheses H1 and H2, supporting the idea that HIIT programs can significantly enhance muscle power and strength in older adults.

When comparing exercise training modalities on muscle power and strength outcomes, it is essential to consider the type of protocol utilised. Most studies on HIIT have adopted MICT assessment protocols, which are appropriate for evaluating changes in aerobic capacity but may not be the most suitable for assessing power and strength adaptations (Weston et al., 2014). Therefore, it is important for future research to assess these outcomes appropriately using tests such as the Herbert 6s PPO, and dynamometers to assess strength and power-focused protocols to provide a meaningful comparison. The observed effects of HIIT on muscle power and strength have been shown to be beneficial, although not primarily targeting these adaptations. A comprehensive review by Laursen and Buchheit (2013a) discusses the mechanisms by which HIIT could improve muscle strength and power. One of the potential mechanisms suggested is the increased activation of fast-twitch muscle fibres during high-intensity efforts, leading to greater neuromuscular adaptations.

In future these methods should be compared against findings from studies such as Fragala et al. (2019), which reported that power training, specifically targeting fast-twitch muscle fibres, led to significant improvements in muscle strength in older adults of up to 43% using resistance training protocols with intensities of 80% of one repetition maximum. Furthermore, the range of improvements in muscle power for studies discussed by Fragala et al. (2019), indicate a large

potential for improvements in muscle power between 14% to 97% following power specific training, with the larger magnitude improvements associated with higher velocity and lower volume protocols. Moreover, there was a strong correlation between the training status of cohorts and response magnitude. I.e., more physically active individuals showed a relatively dampened response. Overall, although HIIT may have efficacy in improving power, it is likely that power focused protocols are likely to be more effective. However, HIIT has demonstrable and substantial effects on aerobic capacity, which are not shared by power focused protocols (Fragala et al., 2019).

In summary, while HIIT may not primarily target strength and power adaptations, it can still improve these areas, particularly when combined with other training modalities. Further research is needed to explore the most effective exercise protocols for optimising strength and power adaptations in older adults, considering factors such as exercise modality, intensity, and duration.

Body fat, fat-free mass (FFM), and lean body mass (LBM) are essential components of overall health, especially in older adults, as they contribute to functional capacity and quality of life. It is important to examine the influence of different exercise modalities and nutritional factors on these components to develop effective interventions for this population. Research has shown that HIIT can lead to improvements in FFM and LBM in older adults, as evidenced by several studies, including those by Boukabous et al. (2019), Bruseghini et al. (2015), and Hwang et al. (2016). These studies have reported increases in LBM ranging from 1.1% to 3.1% and decreases in body fat ranging from 1.5% to 4.4%. These findings support hypotheses H3 and H4, which suggest that HIIT can lead to improvements in FFM and LBM and reductions in body fat in older adults. In comparison, resistance training has also demonstrated significant benefits for body composition in older adults. Liu et al. (2017) found that resistance training led to significant increases in LBM

(ES = 0.56) and reductions in fat mass (ES = -0.46) in this population. Additionally, Peterson et al. (2011) reported an average increase of 1.1 kg in LBM following 18-20 weeks of progressive RT. The results of numerous studies indeed suggest that resistance training and high-intensity interval training (HIIT) may yield comparable benefits in terms of augmenting lean body mass (LBM). For instance, Herbert et al. (2016) reported a 3.0% increase in fat-free mass (equivalent to LBM) in sedentary aging men (mean age: 62 ± 2 years) after a HIIT regimen, while masters athletes in the same study (mean age: 60 ± 5 years) showed a 4.0% increase in fat-free mass following the same exercise intervention. However, it's important to consider longer-term adaptive responses. In training programs, initial gains in LBM are usually substantial but may slow down over time as individuals become more trained.

Adequate protein intake is vital for muscle mass development and sparing. Morton et al. (2018) suggested that older adults may require protein intakes of 1.2-1.6 g/kg/day to optimally support muscle health and function. High-quality protein sources containing all essential amino acids, particularly leucine, may be critical for stimulating muscle protein synthesis (Morton et al., 2018). Energy balance is another crucial factor for supporting muscle mass development and preventing excessive fat accumulation (Wolfe et al., 2018). Consuming an adequate number of kilocalories (kcal) can help ensure that older adults have sufficient energy for muscle protein synthesis and muscle mass preservation.

Considering the combination of exercise modalities and nutritional factors is essential when designing interventions for older adults. The synergistic effects of HIIT and RT, coupled with appropriate protein and kcal intake, may result in optimal improvements in FFM, LBM, and overall body composition. In conclusion, HIIT and RT, along with adequate protein and kcal intake, may be essential for enhancing fat-free mass and lean body mass in older adults. Further

research should explore the optimal combination of exercise modalities and nutritional factors for promoting FFM and LBM gains in this population. Moreover, examining the long-term effects of these interventions on functional capacity and quality of life in older adults is warranted.

6.3 Study 1 Findings

Training frequency is a pivotal factor in designing exercise or training programmes aimed at improving health outcomes (Ratamess et al., 2009). For strength and power training, especially explosive variants, a delicate balance between sufficient rest for muscle recovery and adequate training frequency for stimulation is required, with 2-3 weekly sessions per muscle group typically yielding optimal results (Schoenfeld et al., 2016). Moderate-Intensity Continuous Training (MICT) generally necessitates 150 minutes weekly, spread over 3-5 sessions, ensuring adequate recovery while providing necessary volume for cardiovascular and metabolic adaptations (ACSM, 2011). High-Intensity Interval Training (HIIT), despite its increased intensity, often requires fewer sessions for similar or better outcomes than MICT due to its condensed timeframe, and thus is recommended 2-3 times weekly (Gibala et al., 2012; Weston et al., 2014). Lastly, Sprint Interval Training (SIT), a time efficient form of HIIT, due to its high intensity, should be limited to no more than 2-3 times weekly to prevent overtraining and assure sufficient recovery (Gillen & Gibala, 2014). However, these research findings are based on studies conducted in younger cohorts and may not translate to older populations.

Previous research in HIIT in older adults has been performed using different weekly frequencies of training, e.g., less than two days (Grace et al., 2017; Herbert et al., 2016; Herbert et al., 2017; Knowles et al., 2015; Sculthorpe et al., 2017), 2 days (Hurst et al., 2019; Lepretre et al., 2009), 3 days (Boukabous et al., 2019; Bruseghini et al., 2015; Bruseghini et al., 2020; Molmen et al.,

2012; Sogaard et al., 2017; Sogaard et al., 2019; Storen et al., 2017; Wyckelsma et al., 2017), and 4 days (Hwang et al., 2016; Kim et al., 2017). However, only three of the previous HIIT studies conducted on an older demographic measured muscle power as an outcome, with Herbert et al. (2017) and Sculthorpe et al. (2017), both employing a frequency of once every five days, whereas Hurst et al., (2019), had a higher frequency of twice per week. Importantly, all studies reported an increase in muscle power, with Hurst et al. (2019) reporting the highest improvement at 10.5%. Although, Hurst et al., (2019) employed a HIIT protocol, it was a battery of compound exercises, which reduces the transferability of findings to protocols using running or cycling protocols. Therefore, the research by Herbert et al. (2015b) which identified differences in peak power output recovery between younger and older individual following HIIT at 3 and 5 days of rest is of relevance. As muscle power is a key determinant of physical functioning (Byrne et al., 2016), this was an important facet to investigate in any potential SIT protocol, due to SIT being derived from HIIT, both training forms have significant overlap in physiological stimulus.

When the SIT protocol adopted in the present thesis was utilised in a cycle ergometer mode, different findings were presented when compared with (Herbert et al., 2015b), i.e., that peak power output recovery at 3 and 5 days' was not contingent on age differences, confirming the null hypothesis $H0_6$, suggesting that SIT as performed during the primary research for this thesis, may present some potential advantage in reference to peak power output recovery between sessions. Importantly, this precipitated the possibility of a higher frequency of training for SIT over HIIT, i.e., 2 times week, which is consistent with observations made from Gillen and Gibala (2014). The mechanistic reasons for the disparity in peak power recovery were not investigated. However, the higher exercise volume for the HIIT performed by participants during Herbert et al. (2015b) compared with the lower exercise volume performed during the SIT protocol used in study 1 may have altered the production of reactive oxygen species (ROS) (He et al., 2016),

which are a by-product of mitochondrial respiration (Austin et al., 2011). Although ROS production is required for optimal adaptation, over-produced ROS may hinder performance and adaptations, with changes to optimal levels of ROS production related to fitness levels (Steinbacher and Eckl et al., 2013). Moreover, optimal levels of ROS production change with training habituation, with which ROS regulation is improved (Gomez-Cabrera et al. 2008). Therefore, future research should focus on peak power output recovery at initial exposure and following habitual exposure to SIT exercise.

6.4 Study 2 Findings

Although cycle ergometer SIT was performed during study 1, this method still requires the use of a cycle ergometer. As such, it was determined to be a potential 'barrier to entry' for exercise. Therefore, alternative modes of training were devised with the same SIT protocol, namely, static sprinting, and box stepping. As evidence of static sprinting and box stepping protocols were very limited, internal testing was performed to determine suitable low or no equipment modes of exercise. This yielded static sprinting, and box stepping as potential comparisons with the cycle ergometer mode. As previous research in HIIT and SIT is generally performed on a cycle ergometer, predominantly because cycle ergometers allow for superior experimental control, the static sprinting and box stepping modes were 'validated' against the cycle ergometer mode, comparing for physiological, psychological, and perceptive responses to SIT. The key findings of study 2 were that oxygen uptake was different by a magnitude of ~ 14% between the lowest (cycle ergometer) and greatest (static sprinting) mode, confirming hypothesis $H_{7,}$ with a variation of only ~ 2% in peak heart rate between modes, a result leaning in favour of the null hypothesis H08. Most significantly, the magnitude difference for BLa_{peak} between the lowest (box stepping) and greatest (cycle ergometer) was ~ 48%, with static sprinting approximately in between. The

static sprinting and cycle ergometer modes exerted a group mean BLa_{peak} significantly above 4 $mmol.L^{-1}$, which is the threshold for the onset of blood lactate accumulation (OBLA), confirming hypothesis H9. As previous research by Fiorenza et al. (2018) has demonstrated, metabolic stress is a key mechanistic determinant of adaptations following interval training, this de-emphasised box stepping as a potential mode to promote for future research. Moreover, perceived exertion was higher for static sprinting and the cycle ergometer mode, confirming hypothesis H10.

The finding that oxygen uptake was highest during static sprinting is consistent with what Millet et al. (2012) found in their study, that $\dot{V}O_{2max}$ tends to be higher during running-based exercises compared to cycling, likely due to the greater muscle mass engaged in running. In this case, static sprinting could be viewed as a running-like activity that would involve similar muscle groups.
The observed differences in blood lactate production were dissimilar with what might be expected based on Millet et al. (2012). The higher blood lactate levels observed during cycling, followed by and static sprinting, suggest mechanistically shorter bouts of all-out sprints may be different to general maximal efforts, when focusing on blood lactate production. The difference in lactate production between cycling and running can be explained by the nature of muscle contractions involved in these activities. Cycling predominantly involves concentric contractions, where a muscle shortens under tension, such as the pedaling motion in cycling. Conversely, running involves a balance of both concentric and eccentric contractions (when a muscle lengthens under tension, such as when the foot contacts the ground) (Winter, 2009). It is well-established that concentric exercise generally leads to greater blood lactate accumulation than eccentric exercise, given the same level of perceived exertion (Bijker et al., 2002; Dudley, Abraham & Terjung, 1982). This is likely due to the higher energy cost and lower mechanical efficiency of concentric contractions. In cycling, especially during intense bouts like sprint interval training, the predominance of concentric contractions leads to high levels of anaerobic energy production and,

subsequently, lactate (Paschalis et al., 2011). Conversely, despite running being an intense activity, might produce somewhat lower lactate levels due to its balance of concentric and eccentric contractions (Winter, 2009). Thus, it's plausible that the more concentrically intense activity of cycling could elicit higher blood lactate values over a short time span compared to running. Whereas, during maximal testing, such as in Millet et al., (2012) study, likely leads to larger accumulation over time.

Although previous research into exercise intensity by Ekkekakis et al. (2009) postulated that optimal afferent responses to exercise are likely to be achieved during 'moderately' difficult protocols (approximately 60-70% of maximal aerobic capacity), the findings of study 2 suggest that perceived exertion and exercise enjoyment do not support this principle, as no relationship was observed between aerobic or perceptual exertion and enjoyment, this supports the null hypothesis, $H0_{11}$. Moreover, Bartlett et al. (2011) observed that higher perceived exertion coincided with higher exercise enjoyment when comparing HIIT with an MICT protocol. Both Bartlett et al. (2011), and study 2 observed similar perceived exertions, described as between somewhat hard, and hard, which are harder than moderate on the Borg Scale (Borg, 1982). It is noteworthy, however, to mention that Bartlett et al. (2011) and the findings in study 2 were based on results in physically active participants. However, this precipitates the requirement to analyse perceived exertion and exercise enjoyment in any future research in SIT in older adults, as the results are subject to biases outside of statistical reporting. For instance, during data collection for study 2, many participants found the box stepping to be more difficult technically, precluding participants from being able to consistently exert maximal efforts. This is likely a key contributor to the lower enjoyment experienced during box stepping.

Overall, static sprinting and the cycle ergometer modes were observed to be the most suitable modes for SIT, as similarities between perceived exertion, enjoyment, and HR_{peak} were apparent, with greater oxygen uptake during static sprinting observed compared to cycle ergometry, and higher BLa_{peak} observed for the cycle ergometer over static sprinting. Thus, due to ease of application possible with static sprinting, this mode was examined for long term adaptation in study 3.

6.5 Study 3 Findings

Study 3 investigated the effects of an 8-week Sprint Interval Training (SIT) program on various physiological parameters in physically active older adults. Primarily, the study offered support for H12, documenting a notable 6.8% increase in $\dot{V}O_{2max}$, indicative of improved aerobic performance. Accompanying findings revealed improvements in O2 pulse, Anaerobic Threshold (AT) as a percentage of $\dot{V}O_{2max}$, and Power at $\dot{V}O_{2max}$ by 4.8%, 4.6%, and 3.9% respectively. The study also substantiated H13 and H15, demonstrating a statistically significant 1.8% decrease in resting heart rate and a 5.6% enhancement in peak power output following the SIT regimen, respectively. The analysis of blood pressure, a critical predictor of cardiovascular disease, revealed a beneficial 2.3% reduction in systolic blood pressure (SBP), a 1.3% decline in diastolic blood pressure (DBP), and a 2.1% decrease in mean arterial pressure (MAP), thereby confirming H14 and rejecting H014. Lastly, H16 was not validated, as although a 6.7% increase in postural sway, a measure of balance, was observed across the study's phases, the increase was statistically significant, leading to the rejection of H16 and the endorsement of H016.

Focusing on resting heart rate (RHR) and blood pressure (BP). The post-intervention results showed a modest but statistically significant decrease in RHR from 57 bpm to 56 bpm, a 1.8%

reduction, confirming H13 and rejecting H013. This suggests improved cardiovascular fitness, which is associated with lower mortality risk (Jensen et al., 2012). Furthermore, the 2.7% increase in peak heart rate (HR_{peak}) from 151 to 155 bpm suggests improved maximal exercise capacity (Aspenes et al., 2011). Blood pressure measurements showed a 2.3% decrease in systolic blood pressure (SBP) from 132 to 129 mmHg, a 1.3% decrease in diastolic blood pressure (DBP) from 77 to 76 mmHg, and a 2.1% decrease in mean arterial pressure (MAP) from 95 to 93 mmHg. These changes confirm H14 and reject H014, as they indicate a beneficial effect of SIT on blood pressure, which is a strong predictor of cardiovascular disease (Vasan et al., 2001; Lewington et al., 2002; Roman et al., 2007). The magnitude of these changes aligns with previous research, such as the 2.7% reduction in SBP reported in a meta-analysis of an eclectic category of exercise interventions, ranging from MICT to resistance training (Cornelissen et al., 2010). This corroborates findings in Moderate-Intensity Continuous Training (MICT) and High-Intensity Interval Training (HIIT) interventions, which have demonstrated similar effects. For instance, MICT was found to reduce SBP and DBP by 3.5 and 2.5 mmHg, respectively (Cornelissen and Smart, 2013; Carlson et al., 2014), representing reductions of about 2.6% and 3.2%. HIIT has shown even greater effects, reducing SBP and DBP by 5.0 and 2.0 mmHg respectively in hypertensive individuals (Molmen-Hansen et al., 2012), and by 4.6 and 3.5 mmHg respectively in a broader population (Weston et al., 2014), demonstrating reductions of around 3.4% and 4.5%. Despite the modest changes observed in this study, the findings support the efficacy of exercise interventions, including SIT, in reducing cardiovascular risk.

The hypothesis H15, suggesting an increase in peak power output following an 8-week SIT regimen, was substantiated by the observed 5.6% enhancement in Herbert 6s PPO. Examining the wider context, Herbert et al. (2017) reported an 8.3% increase in absolute peak power output after a six-week cycling intervention in male masters athletes. Although the relative magnitude of this

increase surpasses our study's result, the main difference between the present study and that of Herbert et al. (2017) is the overall interval duration being longer by 300%, albeit at a lower peak interval intensity, these differences are likely dampened when assessing average intensity, as observed in (Yasar et al., 2019), older participants averaged 74%, 71%, and 67% of overall session peak power output during the respective 1st, 2nd, and 3rd sprints. This potentiates the possibility that each spring during the 3 x 20s protocol may have less efficacy in promoting muscle power adaptations, due to insufficient neural activation (Moritani, 1993).

Hurst et al. (2019) employed a varied exercise intervention, resulting in a 10.5% increase in both dominant and non-dominant leg power. This study suggests that diversifying exercises within a SIT regimen could optimize results, though the longer intervention period (12 weeks) might also have contributed to the greater magnitude observed. In contrast, Sculthorpe et al. (2017) reported a 6.7% increase in muscle power using a similar cycling exercise, albeit with a lower intensity (50% peak power output), in sedentary older men. This increment, comparable to our study, highlights the versatility of SIT, showing beneficial effects regardless of initial physical activity level. Our investigation further yielded significant improvements in countermovement jump power and height by approximately 6.9% and 12% respectively. These findings underscore SIT's potential in not only enhancing muscle power but also improving functional performance in older adults.

The all-out nature of the SIT protocol in the present study, which exceeds 100% peak power output relative to $\dot{V}O_{2max}$, adds a layer of complexity to the interpretation of results. The original research conducted in this thesis affirms that physically active older adults can significantly benefit from high intensity SIT. Interestingly, comparison studies such as those by Herbert et al. (2017) and Sculthorpe et al. (2017) involving less intense protocols (40% and 50% peak power

output, respectively) yielded slightly higher increases in power output. These variations in intensity could contribute to the magnitude of improvements, highlighting the potential influence of exercise intensity on peak power output enhancements.

In conclusion, our study corroborates the positive effect of SIT on muscle power in older adults, particularly when using a high-intensity approach. While the magnitudes of improvement differ, the overarching trend across studies underscores the value of SIT in this demographic. Future research should further explore the nuanced interplay between SIT intensity, duration, and exercise variety on the magnitude of peak power output improvements.

The hypothesis (H12) proposed an increase in $\dot{V}O_{2max}$. The results supported this hypothesis, with a notable 6.75% increase in $\dot{V}O_{2max}$. Complementary findings revealed improvements in O2 pulse, Anaerobic Threshold (AT) as a % of $\dot{V}O_{2max}$, and Power at $\dot{V}O_{2max}$, by 4.79%, 4.6%, and 3.93% respectively. The results from our all-out SIT protocol align with several other studies on interval training in older adults, but it's crucial to distinguish between the different types of interval training used. For instance, Boukabous et al. (2019) utilised a HIIT protocol involving treadmill exercise at 90% HR reserve, which is markedly different from our all-out SIT protocol. Despite the difference in intensity and protocol, they also observed an increase in VO2peak in older women. Similarly, Bruseghini et al. (2015) reported a substantial increase in $\dot{V}$O2max of 13.4% using a HIIT protocol. The higher increase might be due to the different exercise modes and intensities between the two studies. However, both studies confirmed the effectiveness of interval training in enhancing $\dot{V}$O2max in older adults.

Studies by Herbert et al. (2016) and Hurst et al. (2019) demonstrated increases in fat-free mass and aerobic capacity, respectively, following HIIT programs. While these results are derived from

HIIT rather than SIT, they highlight the potential of intense interval training in general to enhance aerobic capacity, muscle strength, and overall body composition in older adults. Finally, the studies by Hwang et al. (2016) and Kim et al. (2017) reported significant increases in VO_{2peak} (11.5% and 12.5%, respectively) using a HIIT protocol involving all-extremity ergometer exercise at ~90% HR_{max}. Although these studies used HIIT rather than SIT, the upward trend in $\dot{V}O_{2max}$ across different types of interval training underscores the effectiveness of such training methods in improving aerobic capacity in older adults.

In conclusion, while both SIT and HIIT can enhance aerobic performance in older adults, it's crucial to differentiate between them when interpreting results. Our study supports the effectiveness of all-out SIT in improving aerobic performance, most notably $\dot{V}O_{2max}$, in physically active older adults. However, differences in training protocols, population characteristics, and measurement methods among studies highlight the need for further research to optimise SIT protocols for this demographic.

However, the findings did not confirm H16. Instead, there was a slight increase of approximately 6.74% in postural sway, a measure of balance, over the duration of the study. This increase in postural sway, while small, was contrary to the expected improvement in balance following SIT. While not statistically significant ($p=0.258$, $\eta^2=0.107$), the results indicated a small but consistent increase in postural sway across the phases of the study. Specifically, post-hoc analysis revealed that postural sway was slightly greater at phase B than at phase A ($p=1.000$, $g=0.161$), and slightly greater at phase C than at phase B ($p=0.445$, $g=0.201$). The greatest difference was observed between phases C and A ($p=0.419$, $g=0.390$). These results suggest a progressive increase in postural sway over time, rejecting H16 and supporting H016.

The increase in postural sway observed in this study does not necessarily imply a decline in balance capabilities. Indeed, an increase in postural sway may reflect a more flexible and adaptable postural control system (Richer and Lajoie, 2020). However, it's also possible that the SIT intervention was not sufficient to induce improvements in balance in this population or that the measures used were not sensitive enough to detect such changes.

In the present study, an unexpected increase in Root Mean Square (RMS) sway acceleration, a measure of postural stability, was observed. This outcome is paradoxical to the initial hypothesis that sprint interval training (SIT) would lead to neuromuscular adaptations of the lower limbs, thereby improving postural stability. A potential confounding factor may lie in the geographic location of the study (Lancaster, UK) and the time of year the research was conducted (November 2019 to March 2020). During this period, it's plausible that the serum Vitamin D levels of participants declined, as suggested by Calame et al. (2020). A reduction in Vitamin D status has been associated with increased postural sway (Boersma et al., 2012).

However, the observed increase in postural sway in this study was of a small magnitude and unlikely to be clinically meaningful. Johansson et al. (2017) reported that risks are associated with relatively high path lengths of 400 mm and 920 mm, corresponding to an increased fall risk of 75% to 200% respectively. By contrast, a post hoc determination of the critical difference in RMS sway acceleration in the current study revealed a threshold of 62%, while the changes reported herein were only 11% from phase A to C. Given this, the observed effects are likely artefactual, attributable to either analytical or biological variation. The findings of a previous meta-analysis on the effects of exercise interventions on postural control align with the results of the current study. This meta-analysis reported no benefit of either strength or multi-component exercises, inclusive of balance, endurance, and strength components, on postural control as

measured by the centre of pressure (Low et al., 2017). On the other hand, specific balance training did exert a positive effect on postural control. These findings suggest that the type of exercise prescription is a key determinant of balance adaptations in older adults. Notably, the current study's findings combined with those of Low et al. (2017) suggest that SIT may not be a suitable stimulus for improving postural sway. This corroborates Low et al.'s (2017) recommendations that balance training specifically can improve postural control in older adults. Thus, further investigations into the role of targeted balance training in improving postural control and reducing fall risk in older adults are warranted.

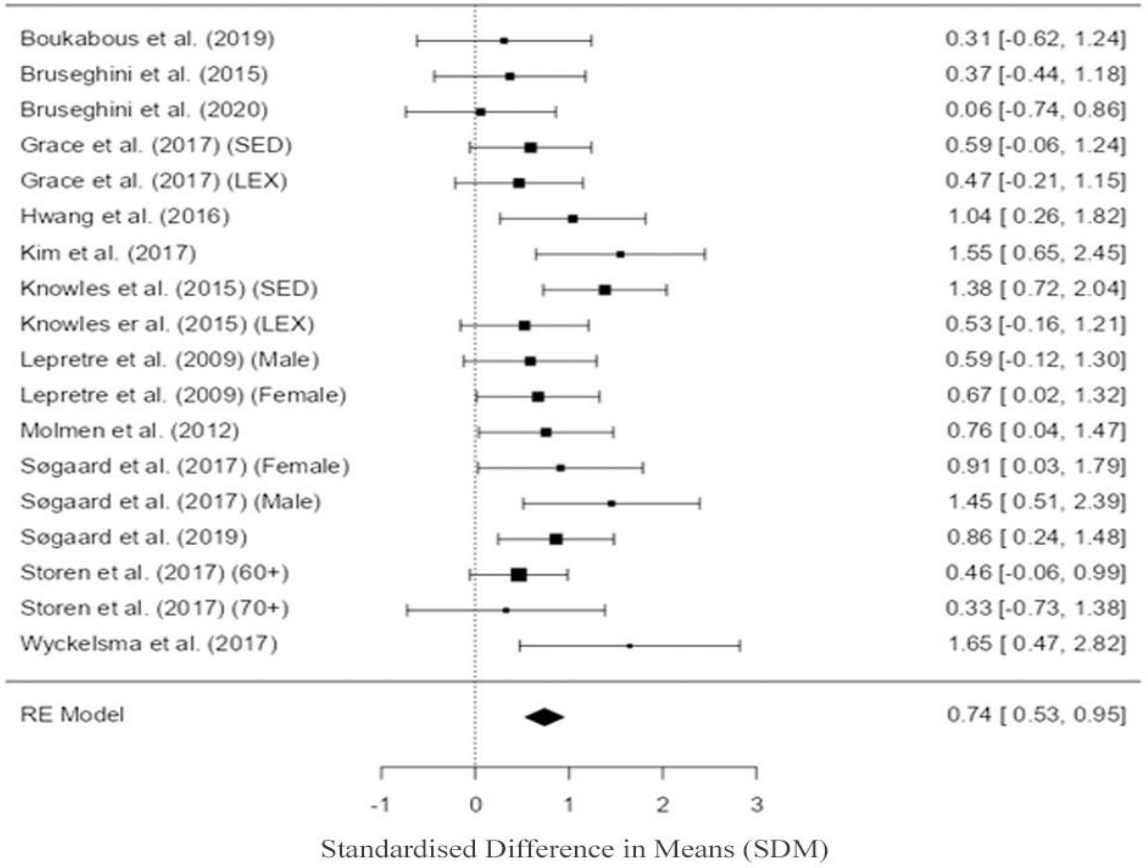


Figure 6.5.1 Summary of studies examining the effect of HIIT interventions on aerobic capacity. Studies are identified and reported with (left to right) authors name, (year of publication), and conditionally, where necessary, (designated group). The size of the filled square symbol for each study represents the weighting for the pooled SDM. SDM for each study are reported alongside upper and lower bounds 95% confidence intervals as SDM [upper bound, lower bound]. The filled diamond indicates overall SDM. SED, sedentary; LEX, lifetime exercisers. 60+, 60–69-year-old group; 70+, 70 years and above group; RE, random effects. Positive SDM favours HIIT in increasing aerobic capacity.

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6.6 Limitations of the Research

The systematic review meta-analysis identified no SIT research in older adults, with the experimental studies (1-3) in this thesis being subject to several limitations, which must be accepted. For instance, the systematic review and meta-analysis was limited by the number of studies eligible, and the analysis for muscle power, muscle strength, fat mass, and lean body mass were conducted with very few studies. Study 1, 2, and 3 were further limited by the combined sex, increasing biological variation (Overfield, 2017). Likewise, study 1, 2, and 3 were conducted with a low sample size, decreasing statistical rigour (Abt et al., 2020). Although guidance was provided to maintain physical activity during study 3, this was not monitored objectively via a physical activity monitor. Furthermore, vitamin D was not controlled for the duration of the study, with seasonal variation likely during the late winter (low) to early spring (lower) cycle of data collection (Webb et al., 2010). This is particularly important as Dahlquist et al. (2015) suggests that higher vitamin D levels appear to have an ergogenic effect on aerobic performance,

muscle performance, and endocrine function, when levels are not deficient, as is observed in most of the UK population in early spring as observed by Webb et al. (2010). This may have reduced the magnitude of adaptations observed in study 3.

6.7 Future Directions for the Research

Beyond correcting for limitations of the studies conducted in this thesis, future research in SIT in older adults needs to consider that SIT can be significantly modified whilst maintaining its low requirements for equipment availability, alongside prescription, and monitoring difficulty. As presented by Buchheit and Laursen (2013a), several key aspects of the SIT protocol can modify outcomes, for instance, less and shorter intervals may be adapted to attract individuals with low to mediocre aerobic fitness levels, for instance two maximal efforts of 15 s has previously been efficacious for improving aerobic capacity (Vollaard and Metcalfe, 2017a). Moreover, Adamson et al. (2018), presented evidence of repeated sprint training with 6 s sprints repeated 10 times improving physical functioning in older adults. Moreover, it may be prudent to introduce more (6-10) and longer (30 s) intervals as those suggested by Hottentrott et al. (2012) and Macpherson et al. (2011) which reported increases of 18.5% (over 12 weeks) and 11.5% (over 6 weeks) respectively in young recreationally trained individuals to increase adaptation for trained individuals. Moreover, adequate protein intake should be a factor to consider during SIT investigations, to ensure protein intake is sufficient for lean body mass gains. Originally, the research proposal for this thesis aimed to examine higher vs lower volume training protocol and nutritional factors affecting adaptation, however due to difficulties with participant recruitment, the research proposal was adapted to its present form as presented. Therefore, future researchers should be prepared to mitigate and/or ameliorate these barriers to research design.

6.8 Conclusions of this Thesis

In conclusion, the thesis provides evidence of ageing mechanisms, and the potential for exercise, across the exercise continuum to provide an attenuating effect on the ageing process. Furthermore, as discussed in the earlier sections of the thesis, the body of evidence surrounding HIIT and its efficacy and application in older demographics are likely useful in promoting aerobic and anaerobic performance and function. Moreover, body composition outcomes are likely beneficial to health outcomes, by reducing body fat levels, which in excess have an association with age accelerating inflammatory markers. This is coupled with potentially positive effects on lean body mass gains. However, some barriers pertaining to how the methods of HIIT that are implemented amongst ageing adults remains. In particular, the difficulty of prescribing specific relative outputs of power as a percentage of aerobic and/or anaerobic output. The SIT modes as studied in this thesis may provide an easier to follow instruction due to its reliance on absolute maximal efforts. Thus, the experimental chapters focused on SIT. The first experimental study found no delay in recovery at 3- or 5-days' recovery with HIIT and observed no differences. Although, absolute differences were observed between younger participants peak power and older participants peak power, the similarity in peak power output recovery profiles provides scope to investigate higher frequency SIT prescription when compared with HIIT protocols in comparable broadly similar cohorts.

Study 2 investigated differences in physiological, psychological, and psychometric analyses when comparing the same SIT protocol in three different exercise modes (static sprinting, cycle ergometer, and box stepping). Findings suggest that overall aerobic stress was highest with the static sprinting and box stepping conditions, whilst heart rate was comparable across conditions. Importantly, metabolic stress measured as circulating blood lactate indicates that the cycling condition was most metabolically stressful, with static sprinting slightly lower, and box stepping

significantly lower in measures of metabolic stress. This result has significance in guiding future directions in research, as the key mechanism by which SIT is purported to increase aerobic capacity is reliant on a stimulus of high/extreme metabolic stress, which demonstrably, box stepping did not provide. Interestingly, increased perceived exertion did not result in decreased enjoyment of the SIT session. These results precipitated the necessity to investigate a suitable mode of SIT, as such, an 8-week SIT intervention protocol with twice weekly static sprinting was investigated in older adults. The results of this study suggest that static sprinting SIT performed twice a week over 8 weeks improves aerobic capacity, muscle power, and hemodynamic function in already physically active older adults. This is like previous findings in HIIT protocols in similar cohorts, but with the likelihood that SIT may be easier to prescribe, it provides a promising avenue of further research, practice, and prescription of SIT within this demographic.

To derive useful applications of SIT protocols within physically active older adults, further investigations should incorporate longer durations of research alongside other modes of exercise, such as cycling. This would enable a better understanding of the mechanisms, as SIT targets mostly peripheral changes to the cardiovascular system alongside acute metabolic adaptations, with increased intervention duration, the comparison against more established MICT and HIIT protocols may become less favourable. Moreover, as study 2 demonstrated, the cycling mode was more metabolically stressful, and as such, may provide an increased adaptive response to the same SIT protocol. Although, the reasoning for including static sprinting over the cycle ergometer was due to the increased requirement of equipment for the cycling mode, and therefore, introducing a potential barrier to adoption. Indicatively, the evidence within this thesis suggests that it is likely that SIT can be effective and easy to apply in already physically active populations for increased physiological functioning. However, further research should consider integrating lesser trained or exercise exposed individuals for SIT tolerance and efficacy.

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Appendices

Appendix A: Ethical Approval Certificate

University of Cumbria
Research Office
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16 October 2018

Our Ref: DC/SB

Zerbu Yasar
MSS
Bowerham Road

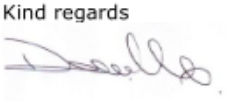
Dear Zerbu

Request for Ethical Clearance – Our Ref: 16/74
Project: SIT in Ageing Populations: Exercise Validation, Adaptation, Enjoyment and Adherence

Thank you for your recent request to update and amendments to your application now placed on file. However, please note that you need to keep the consent form on one side of A4 to ensure that signatures are not detached from what has been agreed/disagreed.

Approval granted through Chair's Action.

Kind regards



Professor Diane Cox
Chair
Research Ethics Panel

Appendix B: Participant Information Sheets and Consent Forms

Appendix B1: Study 1 Participants Information Sheet and Informed Consent Form

University of Cumbria

PARTICIPANT SHEET (PIS)

Participant ID Code: ……

Study title
Peak Power Output Recovery from a Single Session of Sprint Interval Training (SIT) in Older and Younger People.

Invitation paragraph
You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you wish to take part.

Thank you for reading this.

What is the purpose of the study?
The purpose of this study is to determine how long it takes for power recovery from a single session of sprint interval training for older and younger people.

Why have I been chosen?
It is important that we assess as many participants as possible, and you have indicated that you are interested in taking part in this study. You have been invited to participate in this study because you are a suitable candidate as you are between the age ranges of either 18-30 or above 60 years. And are exercising at least 2 or 3 times a week respectively, at a moderate intensity for 30 minutes.

Do I have to take part?
It is up to you to decide whether to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason. If you do decide to withdraw from the study then please inform the researcher as soon as possible, and they will facilitate your withdrawal. If, for any reason, you wish to withdraw your data please contact the researcher within a month of your participation. After this date, it may not be possible to withdraw your individual data as the results may have already been published. However, as all data are anonymised, your individual data will not be identifiable in any way.

Furthermore, termination of your participation in this study will have no repercussions.

What will I have to do?
We will measure your height and weight. You will then be required to complete a questionnaire which will be used to determine your current level of physical activity.

You will be required to attend 4 separate sessions. However, prior to participating in the study, you will be required to undertake a single session induction to familiarise you with the exercise, and to assess you for your power with a 6 second trial. Sessions 1 and 3 will be training sessions where you will be required to perform sprint interval training (SIT). Sessions 2 and 4 will either be 3 days or 5 days after sessions 1 and 3 respectively. Sessions 2 and 4 are designed to test your peak power output (PPO) measured during a 6 second maximal cycle. Details of the training and testing are below. During sessions 1 and 3 you will complete three 20 second maximal sprints interspersed by 3-minute recovery phases, at which you will be required to cycle at a self-paced intensity. At the end, you will cool down for 5 minutes at your own pace. Sessions 2 and 4 will be identical, however instead of performing 20 second sprints you will be required to only perform a single 6 second maximal sprint. Additionally, during the warm up, you will be required to perform short burst of maximal sprinting, approximately 2 seconds each, evenly distributed 3 times over 6 minutes.

Additionally, you will be required to abstain from unaccustomed exhaustive physical activity during your participation in this study. A 24-hour long abstention from alcohol or recreational drugs will be required before attendance for each session.

Will I have to provide any bodily samples (i.e., blood/saliva/urine)?
No bodily samples will be collected during this research.

What are the possible disadvantages and risks of taking part?
You may experience fatigue during and/or after performing the required exercise. Additionally, you may have a slightly increased possibility of experiencing an injury to your muscle during exercise. During exercise, you will have a slightly increased possibility of suffering a cardiac event/accident. A transient increased risk of falling has also been documented by previous researchers.

What are the possible benefits of taking part?
You may experience improvements in your physical and psychological health, although this cannot be guaranteed. You will add to the body of research concerning exercise in older populations.

Will my taking part in this study be kept confidential?
The research team has put several procedures in place to protect the confidentiality of participants. You will be allocated a participant code that will always be used to identify any data you provide. Your name or other personal details will not be associated with your data, for example, the consent form that you sign will be kept separate from your data. All paper records will be stored in a locked filing cabinet, accessible only to the research team, and all electronic data will be stored on a password protected computer. All information you provide will be treated in accordance with the UK Data Protection Act.

What will happen to the results of the research study?
The results of the research study will be used as part of a Postgraduate PhD. The results may also be presented at conferences or in journal articles. However, the data will only be used by members of the research team and at no point will your personal information or data be revealed.

Who has reviewed the study?

The study has received full ethical clearance from the Research ethics committee who reviewed the study. The committee is the University of Cumbria Research Ethics Committee.

What if I want to complain about the research?
Initially, you should contact the researcher directly. However, if you are not satisfied or wish to make a more formal complaint, you should contact Diane Cox, Director of Research Office, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD. diane.cox@cumbria.ac.uk

Contact for further information:
If you require further information, have any questions, or would like to withdraw your data then please contact:

Research Conductor:
Zerbu Yasar
zerbu.yasar@cumbria.ac.uk

Research Supervisor:
Dr Lawrence Hayes BSc (Hons), MSc, PhD, FHEA
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Thank you for taking part in this study. You should keep this participant information sheet as it contains your participant code, valuable information and the research teams contact details.

Participant Consent Form

Title of Investigation: Peak Power Output Recovery from a Single Session of Sprint Interval Training (SIT) in Older and Younger People.

Have you read and understood the information sheet about this study? YES NO
Have you been able to ask questions and had enough information? YES NO
Do you understand that you are free to withdraw from this study at any time, and without having to give a reason for withdrawal? YES NO
Your responses will be anonymised. Do you give permission for members of the research team to analyse and quote your anonymous responses? YES NO

Please sign here if you wish to take part in the research and feel you have had enough information about what is involved:

Signature of participant: ..... **Date:** .....

Name (block letters): .....

Signature of investigator: ..... **Date:** .....

Name (block letters): .....

Appendix B2: Study 2 Participants Information Sheet and Informed Consent Form

University of Cumbria

PARTICIPANT SHEET (PIS)

Participant ID Code: ……

Study title
Differential SIT Exercise Modes in Older and Younger People: Acute Responses to a Single Session

Invitation paragraph
You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you wish to take part.

Thank you for reading this.

What is the purpose of the study?
The purpose of this study is to compare different exercise modes, (cycling, box stepping, and spot running) during, and immediately after, exercise. The exercise intensity will be similar between all modes, as defined by a sprint interval training tempo (this means each interval is completed at maximal effort).

Why have I been chosen?
It is important that we assess as many participants as possible, and you have indicated that you are interested in taking part in this study. You have been invited to participate in this study because you are a suitable candidate for this study because you are between the age ranges of either 18-35 or above 60 years.

Do I have to take part?
It is up to you to decide whether to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason. If you do decide to withdraw from the study then please inform the researcher as soon as possible, and they will facilitate your withdrawal. If, for any reason, you wish to withdraw your data please contact the researcher within a month of your participation. After this date, it may not be possible to withdraw your individual data as the results may have already been published. However, as all data are anonymised, your individual data will not be identifiable in any way.

Furthermore, termination of your participation in this study will have no effect on any aspect of your life.

What will I have to do?

Initially, you will be presented a consent sheet after this information sheet. If you would like to participate you will be required sign this consent form. Alternatively, you can reject the proposal. This will not affect you negatively in any capacity. Subsequently, we will measure your height and weight. You will then be required to complete a questionnaire which will be used to determine your current level of physical activity. Depending on your age and current health you may be requested to partake in a physical conditioning program prior to further participation. This program will aim to ensure you are sufficiently fit to undertake the higher intensity sprint internal training (SIT). This exercise program will require you to complete 150 minutes of exercise per week over 6 weeks. You will be required to abstain from exhaustive physical activity for 24 hours before all testing and training days.

You will be required to participate in three exercise modes; cycling, box stepping and spot running using a SIT protocol that will require you to cycle at 20 seconds maximal interspersed with 3-minute lower intensity recovery phases. Prior to commencement of the SIT exercise, you will be required to warm up for five minutes using the exercise mode that the SIT will be executed in.

The cycling will require you being on a stationary cycle. The bike will be adjusted to fit correctly for you. You will be required to use pedal straps to fasten your feet properly. The box stepping will require you being parallel to an aerobic step, the exercise itself will require you to step on and off this platform at varying speeds. The spot running will consist of you running on the spot at varying speeds.

From the commencement of exercise until completion of exercise energy expenditure will be measured for each exercise modality. Immediately following each of the three sprints, blood lactate concentration, heart rate, and rating of perceived exertion will be recorded. Procedures for each test are detailed below.

Energy Expenditure (EE):
A breath-by-breath gas mask will be attached to your face, placed over your nose. Breath by breath analysis of oxygen consumption and carbon dioxide production (will be measured by an online gas analysis system. You will then be instructed for the appropriate exercise mode.

Blood lactate (BLa):
A sport scientist will thoroughly wash their hands and wear clinical gloves for each new participant. Your earlobe will be subjected to a small laceration with a lancet. A new lancet will be used for each new laceration, if required. Used lancets will be disposed of safely immediately. You will be requested to pause exercise briefly for each laceration. If residual bleeding starts to cause excessive dripping of blood, discretionary use of sterile cotton balls will be used to reduce this via application to the earlobe during exercise. In total, you will be required to provide 9 samples of blood via your earlobe. Each sample will be only a droplet of blood.

Session RPE:
You will be asked to express your subjective opinion of the interval difficulty on the Borg RPE scale (Borg, 1998), immediately after each sprint interval.

Heart rate peak (HR_{peak}):
You will be required to remove your upper body clothing to wear the chest mounted heart rate monitor. This can be achieved alone behind a privacy screen, following live demonstration by a sport scientist. Further assistance will be provided if it is required. Subject to permission from

yourself. Clothing may be worn again for the duration of testing. Heart rate will be measured via a chest strap monitor (Polar, United States) for the 10-second period succeeding each 20-second sprint interval. Following completion of testing the chest strap monitor will be removed. After exercise, you will be asked to fill out a psychological enjoyment questionnaire. Additionally, you will be assessed for postural sway via the use of body movement sensors and muscle force with the use of an electromyogram (EMG).

Postural Sway:
You will have a single sensor placed on your lumbar region (lower back) via the use of strap. You will be asked to stand behind a pre-placed line marker and will look directly at a pre-placed image on a wall 3 metres in front of you while stand quietly, crossing your arms over your chest. You will be required to stand for 30 seconds, during this time you should aim at being as relaxed as possible. Following a single measurement this test will be completed.

Electromyogram (EMG) and Dynamometer:
The researcher will shave any body hair at electrode placement sites, followed by cleaning using isopropyl alcohol. Five electrodes will be attached on various locations of your upper leg (quadriceps and hamstrings). You will be required to sit on a special dynamometer chair. A member of the research team will fasten you into the chair using belt straps. You will be required to place your left leg into a padded strap. You will be asked to push and pull using our left leg at submaximal and then maximal effort for a period of 10 seconds. You will be requested to attempt this between 2-6 times.

Please note that to ensure quality assurance and equity this project may be selected for audit by a designated member of the committee. This means that the designated member can request to see signed consent forms. However, if this is the case your signed consent form will only be accessed by the designated auditor or member of the audit team.

What are the possible disadvantages and risks of taking part?
During exercise, you will be at greater risk of accidental physical injury in comparison with being sedentary. There is also a slightly increased (temporary) risk of a cardiac event during the exercise.

What are the possible benefits of taking part?
We hope that participating in the study will help you by increasing your health, fitness, and appreciation of safer exercise methods. However, this cannot be guaranteed.

Will my taking part in this study be kept confidential?
The research team has put several procedures in place to protect the confidentiality of participants. You will be allocated a participant code that will always be used to identify any data you provide. Your name or other personal details will not be associated with your data, for example, the consent form that you sign will be kept separate from your data. All paper records will be stored in a locked filing cabinet, accessible only to the research team, and all electronic data will be stored on a password protected computer or server. All information you provide will be treated in accordance with the UK Data Protection Act.

What will happen to the results of the research study?
The results of the research study will be used as part of a PhD thesis. The results may also be presented at conferences or in journal articles. However, the data will only be used by members of the research team and at no point will your personal information or data be revealed.

Who has reviewed the study?
The study has received full ethical clearance from the Research ethics committee who reviewed the study. The committee is the University of Cumbria Research Ethics Committee.

What if I want to complain about the research?
Initially you should contact the researcher directly. However, if you are not satisfied or wish to make a more formal complaint you should contact Diane Cox, Director of Research Office, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD. diane.cox@cumbria.ac.uk

Contact for further information:
If you require further information, have any questions, or would like to withdraw your data then please contact:

Research Conductor:
Zerbu Yasar
zerbu.yasar@cumbria.ac.uk

Research Supervisor:
Dr Lawrence Hayes BSc (Hons), MSc, PhD, FHEA
Lecturer in Exercise Physiology
Department of Medical and Sport Sciences
University of Cumbria
Lancaster LA1 3JD
lawrence.hayes@cumbria.ac.uk

Thank you for taking part in this study. You should keep this participant information sheet as it contains your participant code, important information and the research teams contact details.

Participant Consent Form

Title of Investigation: T Differential SIT Exercise Modes in Older and Younger People: Acute Responses to a Single Session

Have you read and understood the information sheet about this study? YES NO
Have you been able to ask questions and had enough information? YES NO
Do you understand that you are free to withdraw from this study at any time, and without having to give a reason for withdrawal? YES NO
Your responses will be anonymised. Do you give permission for members of the research team to analyse and quote your anonymous responses? YES NO
Please sign here if you wish to take part in the research and feel you have had enough information about what is involved:

Signature of participant: ..... **Date:** .....

Name (block letters): .....

Signature of investigator: ..... **Date:** .....

Name (block letters): .....

Appendix B3: Study 3 Participants Information Sheet and Informed Consent Form

University of Cumbria

PARTICIPANT SHEET (PIS)

Participant ID Code: ……

Study title
Physiological, Biomechanical, Psychological, and Behavioural Effects of 8 weeks' SIT over 8 Weeks in Older and Younger Adults

Invitation paragraph
You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether you wish to take part.

Thank you for reading this.

What is the purpose of the study?
The purpose of this study is to compare different exercise modes, such as cycling, box stepping and spot running and the effect this can elicit after exercise. The exercise intensity will range between mild and maximal in intensity.

Why have I been chosen?
It is important that we assess as many participants as possible, and you have indicated that you are interested in taking part in this study. You have been invited to participate in this study because you are a suitable candidate as you are between the age ranges of either 18-35 or above 60 years. Furthermore, you are someone we would consider relatively inactive for sport and fitness; this determination will be made via the use of questionnaire-based data.

Do I have to take part?
It is up to you to decide whether to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason. If you do decide to withdraw from the study then please inform the researcher as soon as possible, and they will facilitate your withdrawal. If, for any reason, you wish to withdraw your data please contact the researcher within a month of your participation. After this date, it may not be possible to withdraw your individual data as the results may have already been published. However, as all data are anonymised, your individual data will not be identifiable in any way.

Furthermore, termination of your participation in this study will have no effect on any aspect of your life.

What will I have to do?
Initially, you will be presented a consent sheet after this information sheet. If you would like to participate you will be required sign this consent form. Alternatively, you can reject the proposal. This will not affect you negatively in any capacity. Subsequently, we will measure your height and weight. You will then be required to complete a questionnaire which will be used to determine your current level of physical activity. Depending on your age and current health you may be requested to partake in a physical conditioning program prior to further participation. This program will aim to ensure you are sufficiently fit to undertake the higher intensity sprint interval training (SIT). This exercise program will require you to complete 150 minutes of exercise per week over 6 weeks. You will be required to abstain from exhaustive physical activity for 24 hours prior to all testing and training days. You will be required to attend a familiarisation session consisting of spot running, box stepping, stationary cycling and countermovement jumping. The details of these exercise forms are detailed below. However, during the familiarisation session, you will not exert maximal effort. Each exercise form will be demonstrated to you by a member of the research team, followed by you practising each exercise for a period of 10 minutes under supervision and instruction by a sport scientist.

You will be required to participate in one of three exercise modes; cycling, box stepping and spot running using a SIT protocol that will require you to cycle at 20 seconds maximal interspersed with 3-minute lower intensity recovery phases. Prior to commencement of the SIT exercise, you will be required to warm up for five minutes using the exercise mode that the SIT will be applied in. Alternatively, you may be placed in a control group that will not partake in mentioned exercise routines. However, in the control group you will be required to maintain habitual physical activity and exercise. The assignment of the groups will be randomised.

The cycling will require you being on a stationary cycle. The bike will be adjusted to fit correctly for you. You will be required to use pedal straps to fasten your feet properly. The box stepping will require you being parallel to an aerobic step, the exercise itself will require you to step on and off this platform at varying speeds (ranging from maximal to self-paced). The spot running will consist of you running on the spot at varying speeds (varying from maximal to self-paced).

Body composition:
Your body composition will be assessed using ultrasonography, recording fat mass (FM) % and lean body mass (LBM). Sites of measurement will differ between men and women. Men will have measurement taken from the chest, abdominal, and thigh. Women will be tested at the upper arm, shoulder blade, and thigh. Body composition measurements will be taken before any intervention associated physical exertion. A thin layer of gel will be applied to measurement sites. Subsequently, the head of the ultrasound wand will be maneuvered over the measurement location in small circles of approximately 5 mm for approximately 5 seconds until a reading is possible. This test will be conducted a week before, during week 4 and a week after your designated exercise program.

RBP and RHR:
You will be required to adopt a supine (laying on your back) position for 10 minutes. Subsequently, four blood pressure and heart rate measurements will be taken using an automatic blood pressure measuring device with 2-minute rest intervals between each measurement. Additionally, you will be required to remove your upper body clothing to wear the chest mounted heart rate monitor. This can be achieved alone behind a privacy screen, following live demonstration by a sport scientist. Further assistance will be provided if it is required, subject to permission from yourself. Clothing may be worn again for the duration of testing. Heart rate will

be measured via a chest strap monitor for the 10-second period succeeding each 20-second sprint interval. Following completion of testing the chest strap monitor will be removed. This test will be conducted a week before, during week 4 and a week after your designated exercise program.

RMR:

A breath-by-breath gas mask will be attached to your face, placed over your mouth. Breath by breath analysis of oxygen consumption and carbon dioxide production will be measured by an online gas analysis system. You will be required to be fasted for a period of 10 hours prior to the RMR test. Only water may be consumed during the fast. Abstention from exhaustive physical exertion will be required for a period of 24 prior. The room will be quiet always with dim lighting. The test will be terminated after approximately 20 minutes. This test will be conducted a week before, during week 4 and a week after your designated exercise program.

PPO:

You will be required to mount the stationary cycle ergometer and strap into your pedals. The bike frame will be adjusted appropriately for your body measurements. You will be asked to cycle for 5 minutes as a warmup. Subsequently, you will be instructed to cycle at your maximum capability for a period of 6 seconds, you will be verbally encouraged during these 6 seconds. Subsequently, you will cool down for a period of 5 minutes. This test will be conducted a week before and a week after your designated exercise program.

Counter Movement Jump (CMJ):

You will be required to step on a force platform. You will then be required to perform three sub-maximal jumps following a 5-minute self-paced spot running warm up. After a two-minute break, 3 separate maximal jumps will be attempted interspersed by 30 seconds' rest. The CMJ technique will require that jumps are performed from a stationary position with your hands placed on your hips throughout. The force platform will be surrounded by exercise mats to provide cushioning and a member of the research team will always act as a "spotter" to minimise the potential of a fall during jump attempts. This test will be conducted a week before, during week 4 and a week after your designated exercise program.

V̇O2max:

A breath-by-breath gas mask will be attached to your face, placed over your mouth. Breath by breath analysis of oxygen (V̇O2) consumption and carbon dioxide production (VCO_2) will be measured by an online gas analysis system. You will be required to mount the stationary cycle ergometer and strap into your pedals. The bike frame will be adjusted appropriately for your body measurements. You will then be required to cycle at 60 watts for a period of 5 minutes as a warm-up. An increase of 20 watts will be applied at the end of every minute-long stage every minute until you reached volitional exhaustion. You will be verbally encouraged during this test. Prior to this test, it is required that you abstain from exhaustive physical exertion for 48 hours. Avoidance of alcohol or non-essential prescription/medicinal drugs will be required for a period of 24 hours before the test. This test will be conducted a week before and a week after your designated exercise program.

Heart rate peak (HR_{peak}):

You will be required to remove your upper body clothing to wear the chest mounted heart rate monitor. This can be achieved alone behind a privacy screen, following live demonstration by a sport scientist. Further assistance will be provided if it is required, subject to permission from yourself. Clothing may be worn again for the duration of testing. Heart rate will be measured via a chest strap monitor (Polar, United States) for the 10-second period succeeding each 20-second

sprint interval. Following completion of testing the chest strap monitor will be removed. Your heart rate peak will be monitored throughout the course of the study.

Postural Sway:
You will have a single sensor placed on your lumbar region (lower back) via the use of strap. You will be asked to stand behind a pre-placed line marker and will look directly at a pre-placed image on a wall 3 meters in front of you while stand quietly, crossing your arms over your chest. Subsequently, postural sway (standing stability) measurement will begin and will require 30 seconds of time, during this time you should aim at being as relaxed as possible. Following a single measurement this test will be completed. This test will be conducted a week before, during week 4 and a week after your designated exercise program.

TUG:
The test will require you to sit on the chair. The "go" command will be given following a countdown from 3 seconds. You will be required to stand up and walk to a cone that is 3 metres away in a straight line, walk around it and back to the chair in a straight line and sit back down whilst being timed. This test will be conducted a week before, during week 4 and a week after your designated exercise program.

Electromyogram (EMG) and Dynamometer:
The researcher will shave any body hair at electrode placement sites, followed by cleaning using isopropyl alcohol. Five electrodes will be attached on various locations of your upper leg (quadriceps and hamstrings). You will then be required to sit on a special dynamometer chair. A member of the research team will fasten you into the chair using belt straps. You will be required to place your left leg into a padded strap. You will be asked to push and pull using your left leg at sub-maximal (low effort) and then maximal effort for a period of 10 seconds. You will be requested to attempt this between 2-6 times. This test will be conducted a week before, during week 4 and a week after your designated exercise program.

Physical activity monitoring (pedometer):
A step-counting pedometer will be attached to your wrist for 7 days during weeks 1, 4 and 8 of your designated exercise programs. You will be required to report step-count data to researchers in the study on request.

Session RPE:
You will be asked to express your subjective opinion of the interval difficulty on the Borg RPE scale (Borg, 1998), immediately after each sprint interval throughout the duration of the exercise sessions.

Blood sampling:
You will be requested to take a seat. The member of the research team assigned with taking your blood will be a trained phlebotomist. You will be required to apply an alcoholic gel to your hands. Your index finger will then be cleaned with an alcohol-based wipe. A blood pressure cuff will be applied to your arm, following a delay of 5 seconds, a lancet needle will be used to lacerate your fingertip (index finger). 3 separate blood droplet samples, less than a milliliter each will be collected during two different sessions, 1 week before the exercise program and the second 1 week following completion. The blood pressure cuff will then be loosened on your arm. A suitable area of your upper arm near a palpable or visible artery near your elbow will be identified. Once an area is identified, an alcohol-based wipe will be applied to this area of the skin. The blood pressure cuff will be re applied. A new cannula will be removed from its

packaging and the needle will be carefully placed into the identified artery; at which time you will informed of the sensation of a sharp scratch. Once the needle is in place, 5 x 5 milliliter tubes of blood will be sampled from this artery 1 week before the start of your designated program and 1 week after. The cannula will then be removed. A cotton ball will be applied to the needle entry point, and a plaster will be applied to hold the cotton in place.

What are the possible disadvantages and risks of taking part?

During exercise, you will be at greater risk of accidental physical injury in comparison with being sedentary. There is also a slightly increased transient (temporary) risk of a cardiac event during the exercise.

What are the possible benefits of taking part?

We hope that participating in the study will help you by improving your health, fitness, and appreciation of safer exercise methods. However, this cannot be guaranteed.

Will my taking part in this study be kept confidential?

The research team has put several procedures in place to protect the confidentiality of participants. You will be allocated a participant code that will always be used to identify any data you provide. Your name or other personal details will not be associated with your data, for example, the consent form that you sign will be kept separate from your data. All paper records will be stored in a locked filing cabinet, accessible only to the research team, and all electronic data will be stored on a password protected computer or server. All information you provide will be treated in accordance with the UK Data Protection Act.

What will happen to the results of the research study?

The results of the research study will be used as part of a PhD thesis. The results may also be presented at conferences or in journal articles. However, the data will only be used by members of the research team and at no point will your personal information or data be revealed.

Who has reviewed the study?

The study has received full ethical clearance from the Research ethics committee who reviewed the study. The committee is the University of Cumbria Research Ethics Committee.

What if I want to complain about the research?

Initially, you should contact the researcher directly. However, if you are not satisfied or wish to make a more formal complaint, you should contact Diane Cox, Director of Research Office, University of Cumbria, Bowerham Road, Lancaster, LA1 3JD. diane.cox@cumbria.ac.uk

Contact for further information:

If you require further information, have any questions, or would like to withdraw your data then please contact:

Research Conductor:
Zerbu Yasar
zerbu.yasar@cumbria.ac.uk

Research Supervisor:
Dr Lawrence Hayes BSc (Hons), MSc, PhD, FHEA
Lecturer in Exercise Physiology
Department of Medical and Sport Sciences
University of Cumbria Lancaster

LA1 3JD
lawrence.hayes@cumbria.ac.uk

Thank you for taking part in this study. You should keep this participant information sheet as it contains your participant code, important information and the research teams contact details.

Participant Consent Form

Title of Investigation: Physiological, Biomechanical, Psychological, and Behavioural Effects of 8 weeks' SIT over 8 Weeks in Older and Younger Adults

Have you read and understood the information sheet about this study? YES NO
Have you been able to ask questions and had enough information? YES NO
Do you understand that you are free to withdraw from this study at any time, and without having to give a reason for withdrawal? YES NO
Your responses will be anonymised. Do you give permission for members of the research team to analyse and quote your anonymous responses? YES NO
Please sign here if you wish to take part in the research and feel you have had enough information about what is involved:

Signature of participant: ..... **Date:** .....

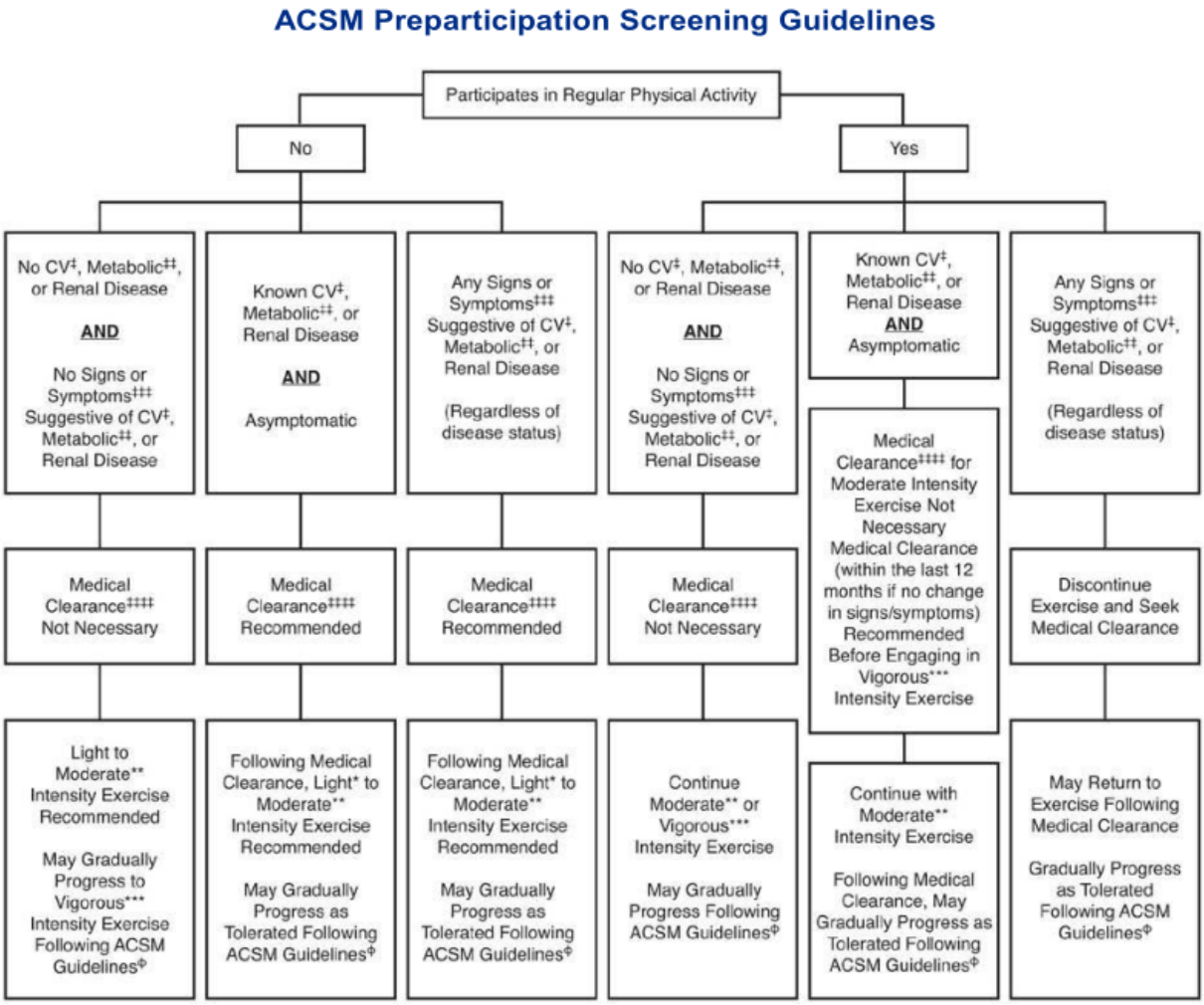
Name (block letters): .....

Signature of investigator: ..... **Date:** .....

Name (block letters): .....

Appendix C: Screenings, Scales and Forms Used Throughout the Studies

Appendix C1: Preparticipation Screening (Riebe et al., 2015)



Riebe D, Franklin BA, Thompson PD, Garber CE, Whitfield GP, Magal M, Pescatello LS. Updating ACSM's Recommendations for Exercise Preparticipation Health Screening. Medicine & Science in Sports & Exercise. *2015; 47(11):2473–2479.*

Appendix C2: PACES Scale (Muller et al., 2011)

Physical Activity Enjoyment Scale (PACES) 8 Questionnaire
Participant ID:
Instruction: Circle the number on the Likert scale that best represents your opinion on the two opposing statements about the sprint interval training (SIT) exercise you just performed. If you require more information, please ask the present researcher for more guidance.

I find it pleasurable	1	2	3	4	5	6	7	I find it unpleasurable
It's no fun at all*	1	2	3	4	5	6	7	It's a lot of fun
It's very pleasant	1	2	3	4	5	6	7	It's very unpleasant
It's very invigorating	1	2	3	4	5	6	7	It's not at all very invigorating

It's very gratifying	1	2	3	4	5	6	7	It's not at all very gratifying
It's very exhilarating	1	2	3	4	5	6	7	It's not at all exhilarating
It's not at all stimulating*	1	2	3	4	5	6	7	It's very stimulating
It's very refreshing	1	2	3	4	5	6	7	It's not at all refreshing

RESEARCHER USE ONLY FROM THIS LINE

Score:

*Inverted scoring. E.g., 1, 4, and 6 on the scale = 7, 4, and 2 points respectively.

Appendix C3: RPE Scale CR–10 (1-10) (Foster et al., 2001)

Rating	**Descriptor**
0	Rest
1	Very, Very Easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	-
7	Very Hard
8	-
9	-
10	Maximal

Appendix D: Publications

sports

MDPI

Article

Peak Power Output Is Similarly Recovered After Three- and Five-Days' Rest Following Sprint Interval Training in Young and Older Adults

Zerbu Yasar [1,*], Susan Dewhurst [2] and Lawrence D. Hayes [1]

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check for updates

Abstract: (1) Background: High-intensity interval training (HIIT) exerts effects indicative of improved health in young and older populations. However, prescribing analogous training programmes is inappropriate, as recovery from HIIT is different between young and older individuals. Sprint interval training (SIT) is a derivative of HIIT but with shorter, maximal effort intervals. Prior to prescribing this mode of training, it is imperative to understand the recovery period to prevent residual fatigue affecting subsequent adaptations. (2) Methods: Nine older (6M/3F; mean age of 70 ± 8 years) and nine young (6M/3F; mean age of 24 ± 3 years) participants performed a baseline peak power output (PPO) test. Subsequently, two SIT sessions consisting of three repetitions of 20 s 'all-out' stationary cycling bouts interspersed by 3 minutes of self-paced recovery were performed. SIT sessions were followed by 3 days' rest and 5 days' rest on two separate occasions, in a randomised crossover design. PPO was measured again to determine whether recovery had been achieved after 3 days or after 5 days. (3) Results: Two-way repeated measure (age (older, young) × 3 time (baseline, 3 days, 5 days)) ANOVA revealed a large effect of age ($p = 0.002$, $n^2_p = 0.460$), with older participants having a lower PPO compared to young participants. A small effect of time ($p = 0.702$, $n^2_p = 0.022$), and a medium interaction between age and time ($p = 0.098$, $n^2_p = 0.135$) was observed. (4) Conclusions: This study demonstrates both young and older adults recover PPO following 3 and 5 days' rest. As such, both groups could undertake SIT following three days of rest, without a reduction in PPO.

Keywords: high-intensity interval training; maximal; older adults; peak power output; recovery; sprint interval training

1. Introduction

High-intensity interval training (HIIT) is characterised by exercise above 80% of maximum heart rate interspersed with lower-intensity recovery phases [1]. Sprint interval training (SIT), a derivative of HIIT, is characterised by maximal exertion, sustained for 30 s or less [2]. HIIT has gained popularity due to improvements in fitness comparable to moderate-intensity continuous training (MICT) [3,4]. Similarly, SIT has produced comparable adaptations to MICT in young adults [2,5], including increased aerobic function, a key a determinant of long-term mortality [6]. With the reported increased enjoyment [7,8], and time efficiency [9], this supports promotion of HIIT or SIT over MICT, by removing potential barriers to exercise adherence.

A limitation of HIIT is that it generally requires intensity-based calculations [1,10,11], which are not required in the use of 'all-out' SIT protocols. Previous HIIT research has shown effects indicative of

improved health with three HIIT sessions per week, in a group with a mean age of 70 years [12], and groups with a mean age of 63 years [13], and both 60–69 years and 70+ years [14]. However, in other studies, similar benefits have been seen with a single session every 5 days, with a mean age range of approximately 60 to 63 years [15–18]. HIIT every five days has been found to increase peak power output (PPO) in older individuals with a mean age of ~61 years [18,19]. PPO is a physiological measure of paramount importance to the older individual due to its importance in physical functioning [20], which elevates the profile of HIIT as a training method to target improvement in power output. However, Herbert et al. [21] observed a delayed recovery of PPO in older participants with a mean age of 63 years. The exercise protocol utilised was a HIIT session comprising of 6 × 30 s intervals working at 50% of PPO, interspersed with 3-minutes active recovery phases. Therefore, some caution is required when prescribing HIIT to older adults. Moreover, it is possible that a delayed recovery in older individuals may transcend between HIIT and its derivative form of 'all-out' SIT, which employs a higher intensity.

Delayed recovery seen in older adults compared to their younger counterparts could be attributed to several biological processes [22]. The driver of the delayed response may be attributed to an age-associated reduction in mitochondrial function [23]. Consequently, a delayed recovery response may be initiated following exercise due to dysregulated reactive oxygen species production and regulation in ageing skeletal muscle [24]. For a more detailed review of the mechanisms of skeletal muscle ageing, we suggest a previous review [25]. The primary effects of ageing on skeletal muscle are sarcopenia, defined as the loss of muscle, and dynapenia, defined as the loss of force production [26]. Although the reduction of muscle strength and mass is a key determinant of physical function [27], muscle power may be a more important determinant of functional capacity [20]. Importantly, this decline in physical function is associated with increased incidence of physical disability, loss of independence, and increased mortality [27].

SIT has demonstrated positive power adaptations in young cohorts [28–32]. This increase in power development appears to be maintained at low-volume SIT training loads of 4–6 repetitions of 10 s maximal sprints when compared to longer 30 s sprints in recreationally active young adults [33]. Additionally, improvements have been observed in aerobic fitness with the prescription of SIT in young cohorts with Wingate SIT protocols consisting of 4–6 repetitions of 30 s maximal efforts [34,35]. Interestingly however, even at significantly reduced training volumes (2 × 20 s sprints), SIT was effective at increasing aerobic function in young populations [36,37]. At present, there is a paucity of data concerning SIT in older adults.

The previously discussed literature justifies the investigation of a low-volume SIT protocol as an intervention to increase overall physical function in older adults. However, before the adaptations to a 3 × 20 s 'all-out' SIT exercise training programme can be explored in older adults, it is imperative to know the duration of rest sufficient for post-training PPO recovery. A previous review has discussed literature on HIIT intersession recovery, concluding optimal recovery to be approximately 48 h following HIIT [11]. However, research discussed in this review concerned young and athletic populations, who likely recover faster due to age-related biological factors [22–24]. Therefore, the present study examined recovery timeframes utilised by Herbert et al. [21]. This is important to avoid maladaptation, but also to avoid a period of reduced muscle power which, as previously discussed, would result in diminished functional capacity. Therefore, the aim of the present study was to investigate PPO after 3 days' and 5 days' recovery following a cycling SIT session in young and older participants. We hypothesised *a priori* that for PPO restoration, older participants would require 5 days' recovery, and young individuals would recover after 3 days.

2. Materials and Methods

2.1. Participants

This study was carried out in accordance with the Declaration of Helsinki and approved by the University of Cumbria Research Ethics Committee (Reference code: 16/74). Written informed consent was obtained from all participants prior to study commencement. A Physical Activity Readiness Questionnaire (PAR-Q) and American College of Sports Medicine (ACSM) pre-exercise participation screening were completed [38]. Participants were habitually physically active, exercising at least twice a week, totalling at least 150 minutes of moderate exercise. Nine older (6M/3F; mean age of 70 ± 8 years, height of 174 ± 9 cm, mass of 70 ± 10 kg) and nine young (6M/3F; mean age of 24 ± 3 years, height of 174 ± 9 cm, mass of 73 ± 7 kg) individuals participated. Abstention from alcohol, caffeine, and exhaustive exercise was required for 24 hours prior to testing sessions.

On the first visit, a baseline PPO assessment was completed. Seven to ten days later, participants performed a SIT session. This exercise was followed by 3 days' rest or 5 days' rest in a randomised crossover design, after which they returned to complete a second PPO measure. Subsequently, participants returned 7–10 days later to complete the other arm of the study (i.e., SIT session with 3 days' or 5 days' recovery).

2.2. Session 1: Baseline Peak Power Output

Following measurement of stature and body mass, participants mounted the cycle ergometer, which was set up according to manufacturer's guidelines (Wattbike Pro, Wattbike Ltd, Nottingham, UK). Subsequently, participants warmed up for 6 minutes at approximately 70 W, interspersed with three ~2 s maximal sprints with an air brake resistance of 8 and a magnetic resistance of 1. Following 5 minutes of passive recovery, participants performed a 6 s Herbert test [39], which involved a maximal sprint from a stationary start, with the air brake set to 10 and magnetic resistance set to 1. Power output was calculated each second for the duration of the test, and PPO was considered as the highest value over 1 s.

2.3. Session 2 and 4: Sprint Interval Training and Peak Power Assessment

As above, participants warmed up for 6 minutes at approximately 70 W, interspersed with three ~2 s maximal sprints with an air brake resistance of 8 and a magnetic resistance of 1. Following 5 minutes of passive recovery, participants remounted the ergometer with the air brake resistance set to 3 and magnetic resistance set to 1. Participants completed 3 × 20 s maximal sprints, interspersed with 3 minutes of active recovery, with strong verbal encouragement during each sprint (Figure 1). A summary of work performed by participants is displayed in Table 1. Upon completion of the final maximal effort interval, a 5-minutes self-paced cool down was performed. Following either 3 or 5 days' recovery, a Herbert 6 s test [39] was repeated to determine PPO.

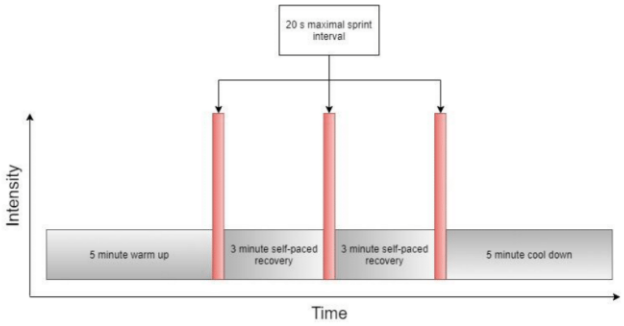

Figure 1. Schematic representation of sprint interval training protocol.

Table 1. Amalgamated peak and mean power completed by older and younger participants during the sprint interval training session. Data are reported as mean and standard deviation (SD).

	Peak Power (W)			Mean Power (W)		
Group	**Sprint 1**	**Sprint 2**	**Sprint 3**	**Sprint 1**	**Sprint 2**	**Sprint 3**
Older	541 ± 135	528 ± 139	498 ± 146	402 ± 93	384 ± 93	362 ± 88
Younger	897 ± 246	828 ± 219	788 ± 215	579 ± 139	513 ± 148	473 ± 156

2.4. Statistical Analysis

Statistics were processed using SPSS version 23.0 (IBM). Following a Shapiro–Wilk's test of normality and Levene's test for homogeneity of variance, a two-way repeated measures ANOVA (age (young vs. older) × recovery time (baseline, 3 days' rest, 5 days' rest)) was conducted. Alpha level was set a priori at $p < 0.05$. Partial eta squared (n^2_p) was used as a measure of main effect, defined as small 0.02, medium 0.13, and large 0.26. Cohen's d was calculated for pairwise comparisons Additionally, an independent samples t-test was conducted to compare weekly mean habitual physical activity at above moderate intensity between older and young participants. Effect size was determined using Cohen's d, defined as small 0.1, medium 0.3, and large 0.5. Data are presented as means ± standard deviation (SD).

3. Results

A large age effect ($p = 0.002$, $n^2_p = 0.460$), small time effect ($p = 0.702$, $n^2_p = 0.022$), and medium interaction effect ($p = 0.098$, $n^2_p = 0.135$) was present for PPO. Younger participants produced greater PPO than older participants (Figure 2). Young PPO for baseline, 3 days' rest, and 5 days' rest was 942 ± 274 W, 921 ± 260 W, and 913 ± 258 W, respectively (Cohen's $d < 0.11$ for all pairwise comparisons). Older PPO for baseline, 3 days' rest, and 5 days' rest was 543 ± 151 W, 561 ± 152 W, and 555 ± 152 W, respectively (Cohen's $d < 0.12$ for all pairwise comparisons). Weekly mean habitual physical activity revealed a large effect between older (417 ± 313 minutes) and young participants (310 ± 65 minutes; t = (8.69) 1.01, $p = 0.342$, $d = 0.68$); equal variances were not assumed ($p = 0.14$).

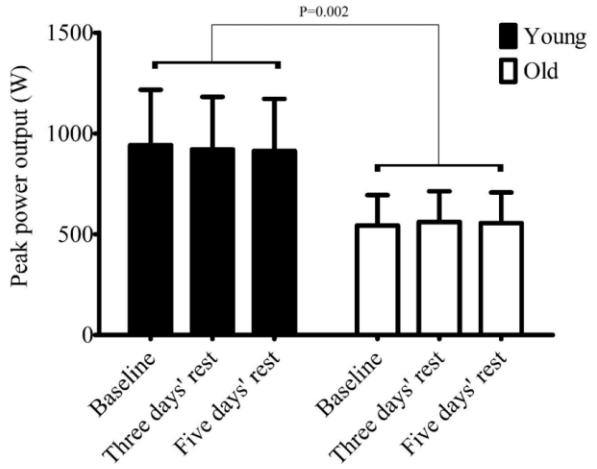

Figure 2. Peak power output (PPO) in young and older participants at baseline, after 3 days' rest, and 5 days' rest following sprint interval training (SIT). The alpha value of $p = 0.002$ indicates a significant difference between older and younger participants.

4. Discussion

The main finding of the present study was that young and older individuals recover PPO from a single SIT session after 3 days' rest. To our knowledge, this is the first study which has investigated recovery following SIT in older adults, and data presented here suggest that recreationally active older adults can include SIT into their physical activity programmes with 3 days' rest, without detriments to PPO.

Current physical activity guidelines for older people suggest that at least 150 minutes of moderate, or 75 minutes of vigorous aerobic exercise should be accumulated weekly in at least 30- or 10-minutes bouts, respectively [40]. Additionally, Chodzko-Zajko et al. [40] suggested a resistance training frequency of twice per week. Currently, however, there is no comparable consensus on HIIT or SIT for older adults. Some evidence has emerged in attempting to provide prescriptive guidelines for HIIT by Herbert et al. [21]. This research demonstrated a delayed PPO recovery from HIIT in older males compared to young males (5 days versus 3 days respectively). Data from the present investigation differ from those of the HIIT-based recovery study by Herbert et al. [21] in that we have demonstrated PPO recovery from SIT after 3 days. This suggests that PPO recovery from HIIT and SIT are different in older adults.

The intensity of the protocol used in the present study was 'all out' or maximal power output, as opposed to the 50% of peak power output (~120% peak oxygen uptake), maintained for 30 s used by Herbert et al. [21]. Given that a higher intensity was utilised in the present study, intensity is unlikely to be the determining factor in PPO recovery duration. The most obvious difference is the greater volume and duration of the exercise protocol employed by Herbert et al. [21]. For instance, the present study used three 20 s maximal intervals, rather than six 30 s intervals at a sustained 50% of maximal effort (i.e., 60 s total work vs. 180 s total work). Previous observations have noted exercise increases the production of reactive oxygen species [41]. Mechanistic investigations suggest that reactive oxygen species are produced as a by-product of mitochondrial respiration, and reactive oxygen species production is positively associated with oxidative phosphorylation [42]. Additionally, previous research has noted the lower overall energy demand of low-volume SIT protocols compared to typical HIIT protocols, even with consideration to the higher intensities used in SIT [1]. This suggests the possibility that the HIIT protocol employed by Herbert et al. [21] was more productive of reactive oxygen species in comparison with the 3 × 20 s SIT protocol used in the present study.

Excessive production of reactive oxygen species has been implicated in deleterious effects via inflammatory pathways to muscle function and performance [43]. Although reactive oxygen species are facilitative of physiological adaptations, it is theorised that there is an optimal reactive oxygen species production threshold, influenced by exercise intensity and/or duration, which may be altered with training status [44] and age [24]. Given that the participants were of a similar training status and age in both the present study and the study conducted by Herbert et al. [21], we tentatively speculate that the training stimulus provided by a 3 × 20 s SIT protocol, as used in the present study, may be more appropriate for reactive oxygen species regulation, as opposed to the protocol used by Herbert et al. [21]. However, this speculation requires further robust mechanistic evaluation within older age groups comparing HIIT and SIT protocols. Furthermore, it is noteworthy to mention that regular exercise has demonstrably improved ROS regulation [44]. Therefore, it is probable that ROS regulation would adapt with exercise habituation.

Strength training studies in older adults demonstrate two or three sessions per week are optimal to facilitate adaptions [45–47]. Similarly, recent evidence suggests that aerobic training adaptations are optimised at a frequency of 3 to 4 times a week in older adults [48]. Strength training and aerobic training have been categorised as opposing ends of an exercise continuum [49]. However, prescribing from guidelines pertaining to either strength or aerobic training is evidently not appropriate when considering the delayed recovery time associated with HIIT [21].

Higher-frequency HIIT in older adults with a mean age of 63 years performed thrice weekly has increased peak oxygen uptake by 3% and 7% for women and men, respectively, over 6 weeks [13], approximately 11% for both 60 to 69 and 70 and above age groups over 8 weeks [14], and approximately

16% over 12 weeks [12]. However, a similar magnitude of improvement was observed, approximately 11% and 8% for previously sedentary and lifetime exercisers with a mean age range of 60–63 years, respectively, utilising lower-frequency HIIT performed once every 5 days for 6 weeks [15]. Importantly, only studies employing lower-frequency HIIT in older individuals have recorded PPO, with increases of approximately 17% in previously sedentary individuals with a mean age of approximately 62 [18], and 8% in master athletes with a mean age of approximately 60 years [19]. These data suggest lower-frequency HIIT may optimise aerobic improvements whilst increasing power in older individuals. Although strength and power are different variables, it is noteworthy to mention that the study by Robinson et al. [12] did not observe any increases to leg press strength following high-frequency HIIT training in older adults with a mean age of approximately 70 years.

Previous research by Adamson et al. [50] demonstrated that repeated (6–10 repetitions) ×6 s sprints increased power by ~13% in an older cohort with a mean age of approximately 66 years, at a frequency of twice per week over a 10-week training intervention. This suggests that neurological adaptations are likely to be well targeted by shorter sprints. However, longer durations of 20 s are associated with increased metabolic stress, which is associated with increased mitochondrial biogenic messenger ribonucleic acid (mRNA) responses when compared to a work matched protocol consisting of shorter 5 s sprints [51]. This suggests that longer sprints are better optimised to increase aerobic function, which decreases overall mortality risk [6]. Due to the divergent stimulus provided by shorter sprints, previous reviews on the topic have justifiably differentiated this type of training as repeated sprint training (RST) [10]. Therefore, at present, we are unaware of any research regarding SIT in older individuals.

We acknowledge the present study is not without limitations. For example, the use of recreationally active older adults was used in the current investigation, which does not permit application of these results to sedentary older adults. However, this recruitment strategy was necessary to ensure safe participation of older participants during maximal exercise [38]. Yet, HIIT has been used effectively in rehabilitation programmes for clinical populations in respiratory [52] and cardiac [53] pathologies, therefore demonstrating efficacy in 'higher-risk' cohorts. Importantly, the current findings may not translate to different modes of exercise, e.g., running, due to the associated increase in eccentric loading [54], which may increase recovery duration from exercise. Therefore, an investigation into recovery from different formats of sprint interval training is justified, with a particular focus on eccentric vs. concentric exercise load. Furthermore, the use of mixed gender sampling decreases the homogeneity of the groups included in the study.

In conclusion, the results of this study suggest that PPO recovery is similar between older and young adults after 3 days' rest following SIT. These data permit SIT prescription in older adults, in the indicative knowledge that recreationally active individuals will be recovered after 3 days' rest. We believe these data can guide prescription of SIT in healthy and active older individuals who may perform SIT following 3 days' rest. As a strength of SIT over HIIT is that prescription is uncomplicated, future research may consider ecologically applicable modes of SIT in older adults, and whether SIT is a viable intervention to improve physical functioning.

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ORIGINAL ARTICLE

Sprint interval training (SIT) reduces serum epidermal growth factor (EGF), but not other inflammatory cytokines in trained older men

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Abstract

Purpose The present study aimed to investigate the effect of age on circulating pro- and anti-inflammatory cytokines and growth factors. A secondary aim was to investigate whether a novel sprint interval training (SIT) intervention (3 × 20 s 'all out' static sprints, twice a week for 8 weeks) would affect inflammatory markers in older men.

Methods Nine older men [68 (1) years] and eleven younger men [28 (2) years] comprised the younger group. Aerobic fitness and inflammatory markers were taken at baseline for both groups and following the SIT intervention for the older group.

Results Interleukin (IL)-8, vascular endothelial growth factor (VEGF), and monocyte chemoattractant protein-1 (MCP-1) were unchanged for the older and younger groups at baseline (IL-8, $p = 0.819$; MCP-1, $p = 0.248$; VEGF, $p = 0.264$). Epidermal growth factor (EGF) was greater in the older group compared to the younger group at baseline [142 (20) pg mL^{-1} and 60 (12) pg mL^{-1}, respectively, $p = 0.001$, Cohen's $d = 1.64$]. Following SIT, older men decreased EGF to 100 (12) pg mL^{-1} which was similar to that of young men who did not undergo training ($p = 0.113$, Cohen's $d = 1.07$).

Conclusion Older aerobically trained men have greater serum EGF than younger aerobically trained men. A novel SIT intervention in older men can shift circulating EGF towards trained younger concentrations. As lower EGF has previously been associated with longevity in *C. elegans*, the manipulative effect of SIT on EGF in healthy ageing in the human may be of further interest.

Keywords Ageing · Cytokines · Exercise · Growth factors · HIIT · Inflammation

Abbreviations

ANOVA	Analysis of variance
BLa	Blood lactate
BMI	Body mass index
EGF	Epidermal growth factor
HIIT	High-intensity interval training
IFNγ	Interferon gamma
IL	Interleukin
MCP-1	Monocyte chemoattractant protein-1
mRNA	Messenger ribonucleic acid
N_2	Nitrogen
O_2	Oxygen
PPO	Peak power output
RER	Respiratory exchange ratio
RPE	Rating of perceived exertion
SD	Standard deviation
SIT	Sprint interval training
TNFα	Tumour necrosis factor alpha
VEGF	Vascular endothelial growth factor

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VO_2 Oxygen uptake
VO_{2peak} Peak oxygen uptake

Introduction

Human ageing involves a loss of function of multiple physiological systems, including the cardiovascular system, respiratory system, musculoskeletal system, and immunosenescence (Rebelo-Marques et al. 2018). Circulating cytokine dysregulation is well recognised as a consequence of biological ageing (Alvarez-Rodriguez et al. 2012). The 'inflamm-ageing' hypothesis suggests that chronic ageing is associated with increased reactive oxygen species and increased basal pro-inflammatory state (Franceschi et al. 2007). Indeed, tumour necrosis factor alpha (TNFα) is greater in 80-year-olds relative to younger individuals and greater again in centenarians. Similarly, interleukin (IL)-6 is elevated with increasing age (Bruunsgaard et al. 1999; Baylis et al. 2013; Kanikowska et al. 2014) while intracellular pro-inflammatory cytokines (including interferon gamma [IFNγ] and TNFα) are seen to be elevated in T cells of older vs young participants (Zanni et al. 2003).

The deleterious effects of ageing on immune function are linked to dysregulation of cytokines which are responsible for the promotion of the pro-ageing senescence-associated secretory phenotype (Coppé et al. 2010). It has been reported the senescence-associated secretory phenotype is promoted by excess body fat associated with increased pro-inflammatory adipokines and cytokines, such as IL-6 and IL-8, alongside cytokines such as monocyte chemoattractant protein-1 (MCP-1), IFNγ, and TNFα (Christiansen et al. 2005; Monzillo et al. 2003; Sharabiani et al. 2011; Vieira et al. 2009). This is further compounded by decreased anti-inflammatory myokine expression, which disrupts inflammatory balance, facilitating pathological developments, including insulin resistance, cardiovascular disease, sarcopenia, chronic kidney disease, neurodegenerative disease, and increased inflamm-ageing of all organs (Muller et al. 2019). Moreover, growth factors, such as vascular endothelial growth factor (VEGF) and epidermal growth factor (EGF), when overexpressed, facilitate increased autoimmune diseases activity and tumorigenesis (Shaik-Dasthagirisaheb et al. 2013; Kasza 2013). Concerning EGF specifically, Meybosch et al. (2019) noted significant inverse correlations between EGF (normalised for body surface area) and age, and EGF and body height. There was a notable and dramatic decrease in EGF post-puberty, causing authors to emphasise the importance of EGF in maturation and growth during the early years of life. What is unknown however, is the influence of physical fitness, physical activity levels, and exercise training on EGF.

Interestingly, whilst the ageing process is omnipresent in humans, physical activity can meaningfully attenuate the development of senescence-associated secretory phenotype (Garatachea et al. 2015). Masters athletes possess superior muscle and cardiovascular function relative to untrained age-matched individuals, but still show decreases in physiological function with increased age, suggesting lifelong exercise can delay, but not prevent, ageing-related changes to physiological systems, including inflammatory cytokine concentrations (Campbell et al. 2019; Duggal et al. 2018; Elliott et al. 2018; Ganse et al. 2018; Pollock et al. 2015).

Formalised physical activity, such as aerobic training and resistance training, have been widely researched for health promoting benefits in older populations (American College of Sports Medicine et al. 2009; Hayes et al. 2015; Hayes and Elliott 2019; Sellami et al. 2019, 2020). Previous reviews have found both aerobic and resistance training to be effective in attenuating senescence-associated secretory phenotype development (Muller et al. 2019; Sellami et al. 2018). Further, a review by Muller et al. (2019) suggests high-intensity interval training (HIIT) also attenuates the senescence-associated secretory phenotype. Previously described by MacInnis and Gibala (2017), HIIT utilises periods of high-intensity exercise interspersed by lower intensity phases of recovery. Generally, even with lower training volumes, HIIT produces similar health benefits when compared to classical forms of aerobic training, and has been deemed time-efficient and enjoyable in various populations (Gibala et al. 2012; Gillen and Gibala 2014; Hayes et al. 2020; Herbert et al. 2017; Hurst et al. 2019; Ramos et al. 2015; Weston et al. 2014). Although HIIT is effective in improving physiological function, it has been suggested the perceived difficulty of performing HIIT coupled with complex prescription may dissuade individuals from adopting HIIT (Biddle and Batterham 2015; Buchheit and Laursen 2013). Yet, a distinct derivative of HIIT, sprint interval training (SIT) offers an easier to prescribe exercise format (i.e. 'all-out'). SIT has been described as enjoyable, tolerable, and easier to prescribe than HIIT, whilst still promoting positive physiological adaptations (MacInnis and Gibala 2017; Olney et al. 2018; Stork et al. 2018; Thum et al. 2017; Vollard et al. 2017; Vollard and Metcalfe 2017). Therefore, it is of interest to the field of exercise science and gerontology to investigate the effects of SIT on immune-modulating cytokines and growth factors (Hwang et al. 2020).

To separate the effect of ageing from any effect of lifelong inactivity on circulating pro-inflammatory cytokines, anti-inflammatory cytokines, and growth factors, we aimed to first establish the effect of age on circulating inflammatory markers and growth factors in well-trained young and older men, by comparing these biomarkers in a cohort of young men, and a cohort of older men who were all aerobically trained. A secondary aim was to examine the effect

of a novel SIT stimuli on older aerobically trained men. It was hypothesised that older men would show elevated pro-inflammatory cytokines relative to a young cohort, and SIT would reduce pro-inflammatory cytokine concentrations.

Methods

Participants

Two cohorts were recruited for this study, younger ($n = 11$; 21–34 years of age) and older ($n = 9$; 63–73 years of age) men, who regularly participated in a weekly minimum of 150 min.wk^{-1} of moderate- or high-intensity exercise for at least 6 months prior to participating in the study and continued habitual physical activity for the duration of the study. Participants were free of exercise contraindicating disease or injury as determined by a Physical Activity Readiness Questionnaire and American College of Sports Medicine pre-exercise participation screening (Riebe et al. 2015). This study was carried out in accordance with the Declaration of Helsinki and approved by the University of Cumbria Research Ethics Committee. Written informed consent was obtained from all participants prior to study commencement and subjects were excluded if they presented with atrial fibrillation. Descriptive statistics for participants are shown in Table 1: Participant anthropometric and performance parameters at baseline (young and older pre-training) and following sprint interval training (SIT; older post-training). Values given as mean (SD)., and further described in the Results section. Participants attended all sessions with exercise-suitable clothing and footwear. The younger cohort attended a single test session whilst the older cohort attended two separate testing sessions 5 days prior to, and 5 days after, the final SIT session of the intervention, which was 8 weeks in duration (Fig. 1).

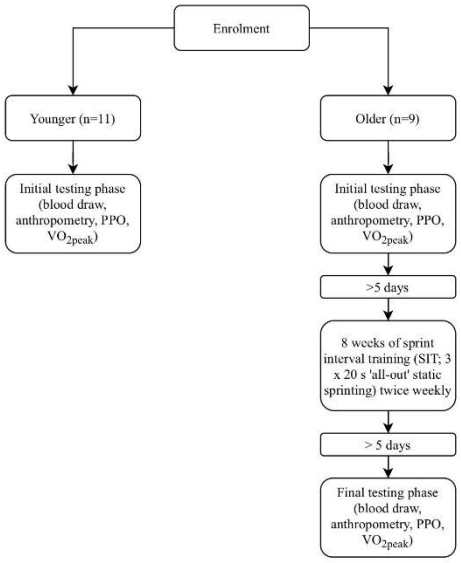

Fig. 1 Schematic representation of the methodological flow. *PPO* peak power output, VO_{2peak} peak oxygen uptake

Blood draws and analysis

Participants arrived at the exercise physiology laboratory between 08.00 and 11.00 h, following an overnight fast and having abstained from strenuous physical activity for a minimum of 48 h. Participants were reminded to maintain standardised conditions prior to each assessment point which included arriving in a hydrated state having abstained from caffeine and alcohol consumption for 24 h. Following

Table 1 Participant anthropometric and performance parameters at baseline (young and older pre-training) and following sprint interval training (SIT; older post-training)

	Young ($n = 11$)	Older	
		Pre-SIT ($n = 9$)	Post-SIT ($n = 9$)
Age (years)	28 (5)	68 (3)[a]	–
BMI (kg m^{-2})	23 (2)	23 (3)	24 (3)[b]
VO_{2peak} (mL kg min^{-1})	55 (11)	39 (6)[a]	41 (8)
PPO (W)	1149 (131)	696 (89)[a]	727 (76)
Resting heart rate (b·min^{-1})	53 (10)	56 (7)	55 (7)
Systolic blood pressure (mmHg)	127 (10)	129 (16)	126 (14)
Diastolic blood pressure (mmHg)	77 (8)	77 (10)	77 (10)

Values given as mean (SD)

SIT sprint interval training, *BMI* body mass index, VO_{2peak} peak oxygen uptake, *PPO* peak power output

[a]Young different to older at the $p < 0.05$ level

[b]Older pre-SIT different to older post-SIT at the $p < 0.05$ level

20 min supine rest, blood was sampled from the antecubital vein using standard venepuncture method into sterile serum separator vacutainer tubes (Becton Dickinson, Rutherford, NJ) that were kept at room temperature in the dark, for 30 min, to allow for clotting, after which samples were centrifuged at 1100 g for 15 min. Serum was then extracted, aliquoted, and stored at − 80 °C until subsequent analysis. Blood samples were collected at the same time of day for each participant to control for biological variation and minimise inter-participant variation. Blood draws were completed prior to any exercise testing.

Anthropometry

Height was measured to the nearest 0.1 cm, and mass to the nearest 0.01 kg using a Seca 286 measuring station (Birmingham, UK), from which body mass index (BMI) was derived by dividing mass by the square of height (kg/m^2).

Peak power output (PPO)

PPO was established using the 6 s Herbert test (Herbert et al. 2015) on an air-braked cycle ergometer (Wattbike Ltd., Nottingham, UK), which consisted of a maximal 6 s sprint from a standing start.

Peak oxygen uptake (VO_{2peak})

At least five min after PPO determination, VO_{2peak} was determined using a Cortex II Metalyser 3B-R2 (Cortex, Biophysik, Leipzig, Germany). Expiratory airflow was achieved using a volume transducer (Triple V® turbine, digital) connected to an oxygen (O_2) analyser. Expired gases were analysed for O_2 with electrochemical cells and for carbon dioxide CO_2 output with an infrared analyser. The Metalyser was calibrated according to manufacturer's guidelines prior to each test. After a 60 min warm-up period, the O_2 and CO_2 sensors were calibrated against environmental air in addition to reference gas of known composition (5% CO_2, 15% O_2, and 80% N_2) with volume calibrated by five inspiratory and expiratory strokes using a 3 L pump. Prior to determination of VO_{2peak}, a chest strap heart rate monitor was attached to participants' chests, with heart rate measured continuously throughout the test (Polar F1, Polar, Finland). The cycle ergometer (Wattbike Pro, Wattbike, UK) was adjusted to manufacturer's guidance. Saddle height was adjusted relative to the crank position and the foot was secured to a pedal with straps with participants' knee at almost full extension (~ 170°). Participants mounted the cycle ergometer, and a rubber face mask was fitted (Hans Rudolph Inc, USA), which was attached to the Cortex II Metalyser 3B-R2. VO_2 and VCO_2 were recorded continuously throughout the test.

Participants completed a 3 min warm-up at an intensity equivalent to ~ 10% of PPO. Subsequently, participants cycled at increasing intensity with 25 W increments each min until they reached volitional exhaustion, with rating of perceived exertion [RPE; 0–10 scale; Borg (1998)] recorded in the last 10 s of each stage. Immediately following volitional exhaustion, participants had their index finger cleaned using a disinfectant wipe, and then a lancet was used to lacerate the fingertip to obtain a blood sample for to measure blood lactate (Lactate Pro 2, Arkray, Japan). VO_{2peak} was confirmed when participants achieved a minimum of any four of the following criteria; VO_2 plateau, RER ≥ 1.10, peak heart rate within 10 beats of age predicted maximum and [BLa] ≥ 8 $mmol \cdot L^{-1}$, final RPE of ≥ 9.

Cytokine array

Cytokine concentrations were quantified in an aliquot of serum utilizing a chip array system (Cytokine array I, Evidence Investigator, Affinity Biolabs, UK) with a sandwich chemiluminescent immunoassay technique for epidermal growth factor (EGF), interleukins (IL-1a, -1b, -2, -4, -6, -8, -10), IFN-γ, MCP-1, TNFα, and VEGF. Method precision and lower/upper limits of sensitivity have been previously reported (Karuppasamy et al. 2011), and quality controls were performed by the manufacturer using three known concentrations for each cytokine.

Exercise training

Older participants attended two SIT sessions per week, 72 h apart, as our pilot work suggested older adults would be suitably recovered from SIT in this timeframe (Yasar et al. 2019). Participants avoided strenuous physical activity 24 h prior to SIT sessions whilst maintaining habitual physical activity according to self-reporting. Participants warmed up for a period of 3 min at a self-paced intensity by performing static running. Participants then performed three 20 s static sprints at an 'all-out' intensity, interspersed by 3 min self-paced recovery phases. Following the final sprint, a 3 min self-paced cool down was performed (Fig. 2). During all sprints, participants were instructed to raise their feet to approximately knee height, with loud verbal encouragement throughout each sprint.

Statistical analysis

Following confirmation of normality by a D'Agostino & Pearson normality test, cytokine data were examined by one-way analysis of variance (ANOVA) or Kruskal–Wallis test as appropriate, with post hoc interrogation by Dunnett's multiple comparison test (younger as comparison group). Descriptive statistics (younger vs older pre-training)

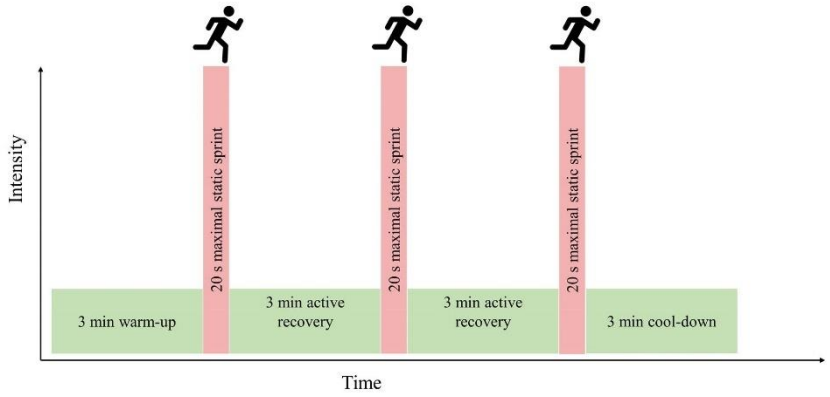

Fig. 2 Schematic representation of the sprint interval session. Participants performed this session twice weekly for eight weeks

and training effects (older group only) were examined by unpaired t test or Mann–Whitney test as appropriate. Fisher's exact test tested for dichotomous differences in whether a cytokine was above or below the minimum level of detection in the older and younger group. Relationships between variables were determined using Pearson's product-moment correlation coefficient. Effect size for paired comparisons is reported as Cohen's *d*, interpreted as trivial (<0.20), small (≥0.20–0.49), moderate (≥0.50–0.79), and large (≥0.80). Parametric data sets are summarised in text as mean and standard deviation (SD) whilst non-parametric are given as median (upper–lower quartile). Figures are presented as grouped dot plots, as recommended by Drummond and Vowler (2011). Alpha level was not set dichotomously as significant or non-significant as recommended by Hurlbert et al. (2019). All figures were generated in GraphPad (5.02, GraphPad Software, USA) or R [version 3.6.1, (R Core Team (2019))] utilizing the *Hmisc* (Harrell et al. 2020) and the *corrplot* (Wei and Simko 2017) packages.

Results

Anthropometric and performance measures

At baseline, older men did not differ from younger men in terms of body mass ($p=0.635$, Cohen's $d=0.13$), BMI ($p=0.070$, Cohen's $d=0.04$) resting heart rate BMI ($p=0.517$, Cohen's $d=0.30$), systolic blood pressure BMI ($p=0.803$, Cohen's $d=0.11$), diastolic blood pressure BMI ($p=0.896$, Cohen's $d=0.06$), or BMI ($p=0.070$, Cohen's $d=0.04$). However, older men did exhibit a lower VO_{2peak} ($p=0.004$, Cohen's $d=1.48$) and PPO ($p<0.001$ Cohen's $d=4.05$; Table 1). The SIT intervention produced a trivial increase in older participants' BMI ($p=0.039$, Cohen's $d=0.12$), a small increase in VO_{2peak} ($p=0.268$, Cohen's $d=0.23$), a small increase in PPO ($p=0.072$, Cohen's $d=0.35$), a small decrease in resting heart rate ($p=0.263$, Cohen's $d=0.40$) a trivial reduction in systolic blood pressure ($p=0.701$, Cohen's $d=0.13$), and a small decrease in diastolic blood pressure ($p=0.347$, Cohen's $d=0.33$).

Cytokines

Of the 12 cytokines measured by chip array, IL-1a, IL-1b, IL-2, IL-4, IL-6, IL-10, IFN-γ and TNFα were frequently below the limit of detection of array methodology, and thus concentrations are not further reported. For clarity, we report on cytokines whereby > 75% of samples returned with values above the lower limit of detection. Ordinal analysis of the data suggests that pro-inflammatory cytokines IL-1a, IL-1b, IL-6 were more frequently observed in the older cohort, whilst classically anti-inflammatory cytokines IL-2 and IL-10 were more often observed quantifiable in the younger cohort. However, Fisher's exact test revealed no differences between younger and older for the frequency of cytokines above or below the limit of detection (Table 2). Pro-inflammatory cytokines IL-8 and MCP-1, and growth factors VEGF and EGF were consistently detected and further described below.

The effect of age and SIT on EGF, IL-8, VEGF and MCP-1, was compared by one-way [condition (younger, older pre-training, older post-training)] ANOVA. EGF showed an effect of condition ($p=0.002$). The effect of condition was examined post hoc by Dunnett's multiple comparison test, with the younger condition as the comparison. Older

Table 2 Cytokine marker state at baseline for young ($n=11$) and older ($n=9$)

Cytokine	Young $N=11$	Older $N=9$	Lower limit of detection (pg mL^{-1})	Accepted (y/n)	p value
EGF	11	9	2.9	Yes	1.000
IL-1a	4	5	0.8	No	0.653
IL-1b	3	4	1.6	No	0.642
IL-2	3	0	4.8	No	0.218
IL-4	0	0	6.6	No	1.000
IL-6	4	6	1.2	No	0.370
IL-8	10	7	4.9	Yes	0.569
IL-10	2	0	1.8	No	0.479
IFN-γ	0	0	3.5	No	1.000
MCP-1	11	9	13.2	Yes	1.000
TNFα	0	0	4.4	No	1.000
VEGF	10	9	14.6	Yes	1.000

Markers were accepted if > 75% of samples returned concentrations > lower limit of detection. p values represent Fisher's exact test for whether the proportion of cytokine detected was different between the young and older group

pre-training EGF was higher compared to the younger group ($p=0.001$, Cohen's $d=1.64$; Fig. 3), whilst the older post-training values were the same as the younger group [$p=0.113$, Cohen's $d=1.07$; younger 60 (12) pg mL^{-1}, older pre-training 142 (20) pg mL^{-1}, older post-training 100 (12) pg mL^{-1}]. There was a large decrease in EGF in the older cohort as a result of SIT ($p=0.101$, Cohen's $d=0.87$). There was no effect of group on remaining pro-inflammatory cytokines [IL-8, $p=0.819$, Cohen's $d=0.28$; younger 9 (3) pg mL^{-1}, older pre-training 8 (4) pg mL^{-1}, older post-training 9 (4) pg mL^{-1}; MCP-1, $p=0.248$, Cohen's $d=0.68$; younger 274 (102) pg mL^{-1}, older pre-training 341 (95) pg mL^{-1}, older post-training 333 (88) pg mL^{-1}] or VEGF [$p=0.264$, Cohen's $d=0.72$; younger 117 (79) pg mL^{-1}, older pre-training 191 (123) pg mL^{-1}, older post-training 152 (80) pg mL^{-1}; Fig. 3b–d]. When examining the magnitude of effect of training in the older group, there was a trivial effect of SIT on MCP-1 ($n=9$; Cohen's $d=0.09$), and a small increase in IL-8 ($n=7$; Cohen's $d=0.30$) and a small decrease in VEGF ($n=9$; Cohen's $d=0.38$).

Relationships between baseline characteristics and circulating cytokines were examined by Pearson's correlation matrix (Fig. 4a). Age was strongly and negatively correlated

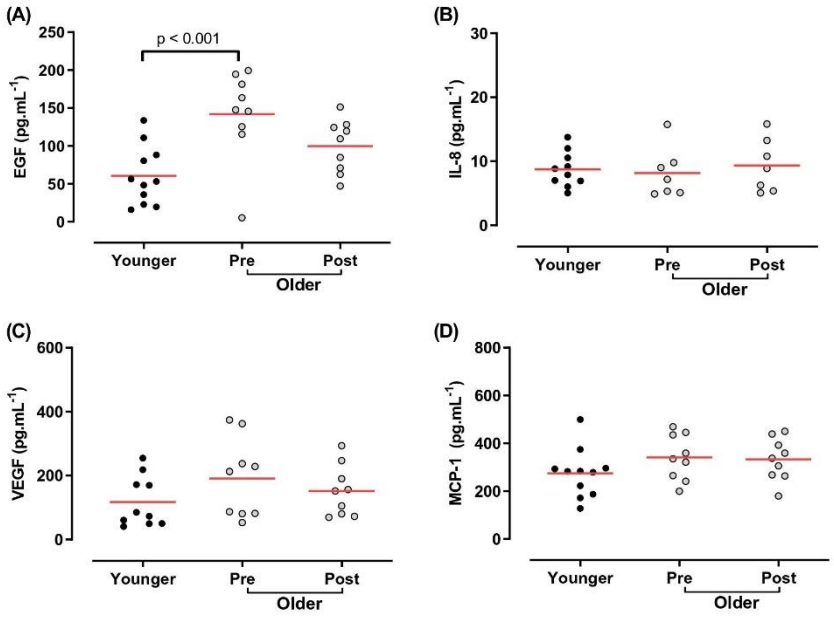

Fig. 3 Cytokine concentrations of young, older pre- and older post-sprint interval training. **a** EGF, **b** IL-8, **c** VEGF and **d** MCP-1. Young shown in black circles, older shown in grey. Red horizontal lines indicate group means

with PPO and VO_{2peak}, and moderately associated with EGF (Fig. 4b). The EGF-PPO relationship was moderate ($p = 0.004$, $r^2 = 0.391$; Fig. 3b), and the EGF-VO_{2peak} relationship was weak ($p = 0.162$, $r^2 = 0.106$; Fig. 4c).

Discussion

The primary findings from the present study were (1) baseline EGF was greater in trained older men compared to younger participants, (2) there was no baseline differences in most (IL-1a, IL-1b, IL-2, IL-6, IL-8, IFN-γ, MCP-1, and TNFα) pro-inflammatory cytokines between trained older men and trained younger men, and (3) we make the novel observation that EGF was reduced to levels of younger men by a novel 8-week SIT intervention in trained older men.

Of the cytokines measured in the present work, only EGF was different between younger and older at baseline. EGF has a well-understood action via the activation of the EGF receptor which is linked to inflammatory responses in terms of wound healing in mouse model keratinocytes, cellular proliferation, chronic kidney disease and tumorigenesis in humans, all of which are negative outcomes of ageing (Choi et al. 2018; Kasza 2013; Rayego-Mateos et al. 2018). However, data presented here should not be read as support of EGF as an activity-independent marker of biological age, as the addition of a novel exercise stimulus reduced EGF concentration in older participants. Indeed, it has been previously shown that overweight sedentary individuals possess lower plasma EGF compared to normal weight controls (Accattato et al. 2017). What physiological effect these alterations in EGF have on healthspan and lifespan can only be speculated at with the data presented here, but it is interesting to observe that a gain-of-function mutation in the EGF receptor promotes longevity in the model organism *C. elegans*, whilst loss-of-function mutations negatively affect longevity (Iwasa et al. 2010; Rongo 2011; Siddiqui et al. 2012).

We demonstrated 8 weeks of SIT-reduced EGF in SIT-naïve, but aerobically trained older men. We are unaware of other studies that investigate the effect of exercise training (i.e. > 1 month) on EGF in older men. However, Accattato et al. (2017) established a single bout of endurance exercise (20 min run at 70% VO_{2peak}) acutely suppresses EGF in younger individuals, yet resistance training has been shown to acutely increase EGF in healthy trained men (Diaz-Castro et al. 2020). Thus, it is clear the type of exercise (resistance vs endurance) influences EGF response after a period of training as recent studies in C2C12 myotubes have shown that EGF receptor inhibition promotes a slow twitch (oxidative) over a fast-twitch muscle phenotype (Ciano et al. 2019). Thus, after resistance training, an increase in EGF would be associated with an increase in muscle protein synthesis

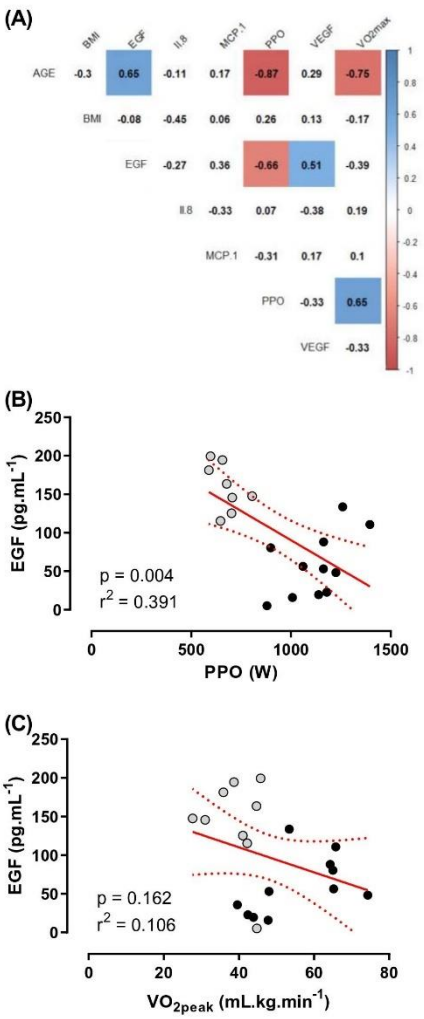

Fig. 4 Correlations between physiological and cytokine markers. **a** Correlation matrix where values indicate r correlation coefficient and filled squares indicate where $p < 0.05$. Shading indicates strength of relationship (blue = positive, red = negative correlation). **b** EGF (pg mL^{-1}) as a function of PPO (W), **c** EGF (pg mL^{-1}) as a function of VO_{2peak} (mL kg min^{-1}). For both (**b**) and (**c**), linear correlation indicated by red line, 95% confidence indicated by red dashed lines. Grey circles indicate older, black indicates younger

and hypertrophy whereas a decrease in EGF after endurance exercise is associated with oxidative adaptation. The clinical significance of these changes in EGF following exercise training is unclear however. Whilst greater EGF receptor prevalence is associated with multiple cancer types (Fisher et al. 2018; Gao et al. 2016; Tokunaga et al. 1995), cardiovascular disease (Makki et al. 2013), and in vitro EGF has been shown to influence cellular proliferation and differentiation rates [included in C2C12 myocytes (Ciano et al. 2019)], it is difficult to speculate concerning the biological role that post-SIT EGF suppression exerts in older men here.

Ageing is associated with a fast-to-slow muscle fibre type shift (Brunner et al. 2007; Deschenes 2004), as is chronic endurance training (Hawley et al. 2014), and this observation is maintained in lifelong endurance-trained older individuals (Dubé et al. 2016). In a cohort of both healthy controls and chronic obstructive pulmonary disease patients, greater muscle EGF messenger ribonucleic acid (mRNA) expression was associated with fewer slow-twitch muscle fibres and lower VO_{2peak} (Ciano et al. 2019). Interestingly, our data suggest lifelong endurance training into older age is associated with higher EGF expression than younger adults, yet a relatively high VO_{2peak}. The reasonably expected large percentage of slow-twitch fibre type expression in our trained older participants may correlate with higher EGF expression, and the introduction of a 'fast twitch' promoting training stimulus could thus be speculated to induce the witnessed depression in circulating EGF, yet muscle biopsies would be required to confirm the fibre type shift.

Ageing is associated with an increased basal expression of circulating pro-inflammatory cytokines (Michaud et al. 2013). A recent meta-analysis concluded that chronic (at least 4 weeks) aerobic exercise in middle aged and older individuals decreased pro-inflammatory markers TNFα and IL-6 (Zheng et al. 2019). In addition, low physical activity levels and high sitting time increase overall risk of death from inflammation-related chronic disorders in people aged > 60 years (Cabanas-Sanchez et al. 2018). In line with this, our results demonstrate that aerobically trained older men possess low circulating concentrations of several pro-inflammatory cytokines. Our data are thus in line with the hypothesis that basal inflammation seen in older individuals may be partly inactivity-induced, and not a result of chronological ageing per se. This is supported by the fact that several of the cytokines reported here were below assay limits of detection, our participants did not show the elevated systemic inflammation typically seen in inactive older populations.

VEGF is a potent angiogenetic factor (Apte et al. 2019) and is essential for exercise-induced angiogenesis and subsequent improvements in performance (Wagner et al. 2006). In younger adults, resting VEGF was not changed following a HIIT intervention of 6 weeks (Żebrowska et al. 2019). VEGF positively associates with age in adults (Ruggiero et al. 2011) and has previously been reported to be increased in sedentary older individuals relative to lifelong exercisers, and further increased in sedentary individuals by 6 weeks of HIIT (Grace et al. 2015). We see no difference either in younger vs older trained individuals, or any pre-to-post training effect in our older population. Thus, any effects of ageing on circulated VEGF may be negated by lifelong exercise behaviour. In a similar manner, MCP-1 positivity associates with age in mice and is elevated in older frail individuals relative to non-frail age-matched controls (Yousefzadeh et al. 2018). As MCP-1 was not elevated in our cohort of trained older individuals relative to our younger population, this provides further support of the use of MCP-1 and VEGF as a marker of biological age, however, the addition of an inactive ageing control group to our model is needed to confirm this.

Some limitations to our study design should be acknowledged. We specifically sought to examine trained older individuals, comparing them to trained younger adults to remove any effect of inactivity on ageing. However, the addition of an inactive older group would have been a useful addition to confirm inactivity-associated ageing changes in pro-inflammatory cytokines and growth factors that others have reported. Likewise, a young training group would have provided insight as to whether they possess more plasticity with regards to serum cytokine concentrations. In addition, this study did not include women, and therefore, findings cannot be extrapolated to women. Having multiple cytokine markers below useful limits of detection was a methodological weakness of the approach that we have utilised here, and future studies will need to consider the use of high-sensitivity biochip cytokine arrays, individual ELISA per marker, or the use of multiplex ELISA techniques, however, these methodological approaches are associated with greater resource commitments. In addition, the present study did not verify objectively measured physical activity of participants during the study. Instead, the present study relied on self-reporting, which is subject to self-reporting bias.

In conclusion, here we make novel observations on the state of circulating pro- and anti-inflammatory markers in trained older individuals. EGF was greater in endurance trained older individuals compared to younger men, however, the addition of a novel SIT intervention in older men can shift circulating EGF towards trained younger concentrations. As EGF has previously been associated with longevity in *C. elegans*, the manipulative effect of SIT on EGF in healthy ageing in the human may be of further interest.

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Compliance with ethical standards

Conflicts of interest We declare no conflict of interest or competing interests.

Ethical approval Ethical approval was obtained for this study and all participants provided informed consent. All authors have read the manuscript and consent for this work to be published. Data can be made available on request. Code details are not applicable within this manuscript, but all software details are given.

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High intensity interval training (HIIT) as a potential countermeasure for sarcopenia: A scoping review

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Running head: HIIT and sarcopenia scoping review.

Abstract

Background: Sarcopenia is defined as a progressive and generalized loss of skeletal muscle quantity and function associated predominantly with ageing. Physical activity appears the most promising intervention to attenuate sarcopenia, yet physical activity guidelines are rarely met. In recent years high intensity interval training (HIIT) has garnered interested in athletic populations, clinical populations, and general population alike. There is emerging evidence of the efficacy of HIIT in the young old (i.e. seventh decade of life), yet data concerning the oldest old (i.e. ninth decade of life onwards), and those diagnosed with sarcopenic are sparse.

Objectives: In this scoping review of the literature, we aggregated information regarding HIIT as a potential intervention to attenuate sarcopenia.

Eligibility criteria: Original investigations concerning the impact of HIIT on muscle function, muscle quantity or quality, and physical performance in older individuals (mean age ≥60 years of age) were considered.

Sources of evidence: Five electronic databases (Medline, EMBASE, Web of Science, Scopus, and the Cochrane Central Register of Controlled Trials [CENTRAL]) were searched.

Methods: A scoping review was conducted using the Arksey and O'Malley methodological framework (2005). Review selection and characterization were performed by two independent reviewers using pretested forms.

Results: Authors reviewed 1063 titles abstracts for inclusion with 74 selected for full text review. Thirty-two studies were analyzed. Twenty-seven studies had a mean participant age in the 60s, two in the 70s, and three in the 80s. There were 13 studies which examined the effect of HIIT on muscle function, 20 which examined muscle quantity, and 14 which examined physical performance. HIIT was generally effective in improving muscle function and physical performance, with more ambiguity concerning muscle quantity.

Conclusions: Most studies presented herein utilized outcome measures defined by the European Working Group on Sarcopenia in Older People (EWGSOP). However, there are too few studies investigating any form of HIIT in the oldest old (i.e. ≥80 years of age), or those already sarcopenic. Therefore, more intervention studies are needed in this population.

Key points

A variety of intensity prescriptions were utilized in previous experiments, which included 'all-out' effort, percentage of maximal heart rate, perceived a percentage of peak oxygen uptake, percentage of intensity at termination of a ramped exercise test, percentage of peak instantaneous power, rating of perceived exertion, and percentage of maximum gait speed.

Twenty-seven studies had a mean participant age in the 60s, two in the 70s, and three in the 80s. There were 20 studies which examined the effect of HIIT on muscle function, 21 studies which examined the effect of HIIT on muscle quantity, and 12 studies which examined the effect of HIIT on physical function (which are the outcomes used to diagnose sarcopenia).

No previous investigation had considered HIIT in a sarcopenic or pre-sarcopenic population, and only three studies were in the oldest old humans.

1. Introduction

1.1 Rationale

Sarcopenia is a progressive skeletal muscle disorder, characterized by reduced skeletal muscle quantity and function which is associated with a range of negative health outcomes including frailty, falls, reduced quality of life and mortality [1,2]. In addition to these individual health impacts, sarcopenia places a considerable economic burden on healthcare systems with the associated costs in the UK estimated at £2.5 billion per year [3]. Taken together, these effects highlight the need to develop treatment strategies to counteract the deleterious consequences of sarcopenia.

To date, and with no specific drugs approved for the treatment of sarcopenia, resistance exercise training is widely recommended as the front-line treatment for sarcopenia [4]. Given the multi-faceted impact of the problem however, exercise programmes for sarcopenic older adults often involve a combination of exercise modes [5] with the aim of simultaneously improving muscular function and cardiorespiratory fitness [6]. Offering a range of alternative exercise training approaches which can simultaneously improve multiple outcomes (e.g., muscle strength, physical performance, and cardiorespiratory fitness) could help to engage a greater number of individuals in an exercise programme.

Recently, high intensity interval training (HIIT) has been shown to exert cardioprotective effects, equal or superior to the traditional 150 $min \cdot wk^{-1}$ moderate aerobic training advocated in physical activity guidelines [7–12]. However, much less is known about how HIIT could improve elements of muscular structure and function. A recent narrative review [13] outlined several mechanistic explanations as to why HIIT *might* be anabolic in nature. These authors called for further investigation of HIIT in populations of different age groups and training status to explore this phenomenon further. Moreover, they proposed HIIT may be beneficial in middle and older age where physical conditioning (i.e. aerobic fitness) and increased muscle quantity were simultaneously desired. Whether HIIT could provide the necessary improvements in muscle quantity, quality, and strength, in addition to cardioprotective effects however, remain unclear [14]. The potential for HIIT to simultaneously induce improvements in cardiometabolic health and muscular health is an appealing strategy. However, until now there has not been a comprehensive review of HIIT within older adults pertaining to sarcopenia using a systematic search strategy.

Given that older adults exhibit the highest percentage of individuals classified as inactive or sedentary [15], and even fewer complete the recommended muscle strengthening exercise volume [16], it is apparent current exercise guidelines for older adults are not being met. Therefore, an alternative or supplementary exercise mode would be beneficial [17,18]. HIIT is reportedly enjoyable [19], can be completed without gym equipment [20–22], and deliver self-perceived health and fitness improvements [7]. However, before HIIT can be proposed as a viable countermeasure to sarcopenia, it is important to consider the existing literature in terms of methodologies, quality of research, and heterogeneity, to determine whether a systematic review and meta-analysis is possible. A comprehensive review of HIIT and its effect on sarcopenia is important for clinicians and exercise practitioners to ensure they are equipped to support community-dwelling older adults and their families/caregivers. Therefore, it seemed prudent to conduct a scoping review in this area to map the existing literature in terms of the volume, nature, and characteristics of the primary research [23]. We used a scoping review rather than systematic review and meta-analysis because our aim was not to ask a precise question and were more interested in the characteristics of investigations conducted [24]. Moreover, the topic has not yet been extensively reviewed and may have been complex or heterogeneous in nature. If existing research was heterogenous, a systematic review and meta-analysis would not have been possible, and therefore we opted to scope the area in this manuscript [25].

1.2 Objectives

We aimed to provide an overview of existing literature relating to elements of sarcopenia and pre- and post-HIIT in older adults. The four specific objectives of this scoping review were to (1) conduct a systematic search of the published literature for the effect of HIIT on muscle strength, muscle quantity or quality, and physical performance (aligned to the 2018 operational definition of sarcopenia[1]) in older adults, (2) map characteristics and methodologies used and classified as 'HIIT' within the interventions, (3) outline the range and characteristics of outcome variables used, and (4) provide recommendations for the advancement of the investigative area.

2 Methods

2.1 Protocol and registration

The review was conducted and reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for scoping reviews (PRISMA-ScR) guidelines [26] and the five-stage framework outlined in Arksey and O'Malley [23]. A review protocol was not published.

2.2 Eligibility criteria

Studies that met the following criteria were included: (1) involvement of human participants with a mean age of ≥ 60 years (considered the start of old age [27]); (2) not a review; (3) an intervention which included bouts of high intensity exercise interspersed with periods of recovery, including exercise defined as HIIT or sprint interval training (SIT). We defined high intensity as exercise >85% peak oxygen uptake (VO_{2peak}) or 85% maximal heart rate (HR_{max}) or equivalent perception-based approaches; (4) employing an intervention design and include an exercise training period of >2 weeks; (5) including HIIT in isolation or performed in combination with another form of exercise; (6) including outcome measures related to either (i) muscle function (either strength or power), (ii) muscle quantity, or (iii) physical performance.

2.3 Search strategy

The search strategy consisted of a combination of free-text and MeSH terms relating to 'high-intensity interval training', 'sarcopenia' and 'older adults' which were developed through examination of previously published original and review articles (e.g., screening of titles, abstracts, keywords). Filters were applied to ensure that only records published in English language involving human participants were included in the search results. Full search terms and the complete search strategy can be found in the online supplementary material associated with this article (Supplementary material 1).

2.4 Information sources

Five electronic databases (Medline, EMBASE, Web of Science, Scopus, and the Cochrane Central Register of Controlled Trials [CENTRAL]) were searched to identify original research articles published from the earliest available up until 12th March 2020. Reference lists from included studies and previously published review articles were examined for potentially eligible papers.

2.5 Study selection

Data were extracted by two reviewers (LH & CH) independently and compared in an unblinded and standardized manner. Once each database search was completed and manuscripts were sourced, all studies were downloaded into a single reference list with duplicates removed. Titles and abstracts were then screened for eligibility and full texts were only retrieved for studies with HIIT incorporated. Two reviewers then read and coded all the included articles using the PEDro scale [28]. Full texts were then thoroughly assessed using the complete eligibility criteria with first (LH) and last (CH) authors confirming inclusion and exclusion. Following this quality assessment, the same reviewers read and coded each of the studies and assessed the following moderators: design method (randomized control trial; RCT, controlled trial; CT or uncontrolled trial; UCT), combined or HIIT in isolation, and outcome variable. Furthermore, participant descriptions and training programme variables were extracted with as much detail provided by the authors. Any disagreement between reviewers was discussed in a consensus meeting, and unresolved items were addressed by a third reviewer.

2.6 Data items

Data extracted from each study included sample size, group descriptions, study design, analysis method, and outcome data. Methodological quality was assessed using the modified 0–10 PEDro scale [28]. The primary outcome variables were defined as muscle strength or power, muscle quantity or quality, and physical performance, pre- and post-intervention. There was heterogeneity in study inclusion criteria, interventions, assessment tools, and outcomes, thus a pooled analysis was not appropriate.

3 Results

3.1 Study selection

Following the initial database search, 1267 records were identified (Figure 1). Once duplicates were removed, 1063 titles and abstracts remained, and were screened for inclusion, resulting in 74 full-text articles being screened. Of these, 42 were excluded and 32 remained.

INSERT FIGURE 1 ABOUT HERE

Figure 1. Schematic flow diagram describing exclusions of potential studies and final number of studies.

3.2 Study characteristics

Of the 32 studies included, 14 were RCTs [8,29–41], one was a quasi-experimental, non-randomized, single-blinded controlled study [42], 16 were observational cohort studies [43–58], and one was a pilot study (although randomized; [59] (Table 1). Where a study had multiple outcome measures, they were examined separately. Three out of 32 (9%) included HIIT in a multicomponent intervention. Sixteen studies included HIIT on a cycle ergometer, six included HIIT on a treadmill, seven included resistance exercise HIIT (including bodyweight exercises), two included HIIT on an elliptical trainer, and one study did not detail the intervention. Three studies used an 'all-out' intensity, 15 used a percentage of HR_{max} or heart rate reserve (HRR) to prescribe intensity, four used a percentage of VO_{2peak} to prescribe intensity, three used a percentage of intensity at termination of a ramped incremental exercise protocol to prescribe intensity, four used percentage of peak power output to prescribe intensity, one used the Borg scale to prescribe intensity, one study used a percentage of maximum gait speed to prescribe intensity, and one study did not detail the intervention. Twenty-seven studies had a mean age in the 60s, two in the 70s, and three in the 80s. One study considered frail participants. There were 20 studies which examined the effect of HIIT on muscle function, 21 studies which examined the effect of HIIT on muscle quantity, and 12 studies which examined the effect of HIIT on physical function (Figure 2). Several studies investigated more

than one parameter, thus why the sum of the studies above is greater than the number of included studies.

*****INSERT TABLE 1 ABOUT HERE****

Table 1. General study information of investigations concerning HIIT and sarcopenia outcomes.

*****INSERT FIGURE 2 ABOUT HERE*****

Figure 2. Schematic representation of frequency of outcome examined (n=53) within the 32 included studies concerning HIIT and sarcopenia outcomes.

3.3 HIIT and muscle function

There were 20 studies which examined the effect of HIIT on muscle function using one or more of the criteria outline by EWGSOP [1] (Table 2). Of these, 18 measured muscle strength, and five measured muscle power (some studies measured both, thus why this total is not 20). Of those reporting strength, four used the handgrip test, one used a 30 s arm curl test, five used a 30 s chair stand test, four used the 5 repetitions chair stand test, one used a 10 repetition chair stand test, two used knee extensor isokinetic dynamometry, one used a strain gauge for the knee extensors, four used a leg press, two used a chest press, three used a knee extension machine (which was not a dynamometer), and one used *latissimus dorsi* pull-down, horizontal row, and shoulder press. Of the 18 studies examining strength outcomes, 15 reported ≥1 strength parameter having been improved by HIIT compared to pre-training or compared to a moderate intensity continuous training (MICT) or non-exercise control. Of the remaining three [38,39,54], they all reported strength had improved more in a combined aerobic and resistance training group than a HIIT group.

There were five studies which examined the effect of HIIT on muscle power, all through determination of peak power output. Of these, two measured leg extensor power, two measured peak

power output from a 6 s cycle ergometer test, and one measured leg press force-velocity profiling. Of these studies, all reported improved power output post-HIIT.

*****INSERT TABLE 2 ABOUT HERE****

Table 2. Summary of study details concerning HIIT and muscle function.

3.4 HIIT and muscle quantity or quality

There were 21 studies which examined the effect of HIIT on muscle quantity or a surrogate (fat free mass, lean mass, thigh volume; Table 3). Of these, 13 measured whole body lean mass by dual-energy X-ray absorptiometry (DEXA), nine measured leg lean mass by DEXA (of these, all nine also reported whole body lean mass), one measured whole body lean mass by air plethysmography, one measured *M. vastus lateralis* muscle thickness by ultrasonography, two measured quadriceps muscle volume by magnetic resonance imaging (MRI), two measured quadriceps cross-sectional area (CSA) or anatomical CSA (ACSA) by MRI, one measured thigh muscle area by peripheral quantitative computed tomography (pQCT), and six measured whole body lean mass by bioelectrical impedance analysis (BIA). Of the 22 studies examining muscle quantity or quality outcomes, nine reported ≥1 muscle quantity parameter was improved by HIIT, 12 reported no difference in ≥1 measure from pre-intervention or versus a no exercise control, one reported inferior adaptation following HIIT compared to a group undertaking resistance training in ≥1 measure, one study reported lean mass was lost post-HIIT to a similar extent as a non-exercise control, and one did not report post-intervention lean mass.

*****INSERT TABLE 3 ABOUT HERE****

Table 3. Summary of study details concerning HIIT and muscle quantity or quality.

3.5 HIIT and physical performance

There were 12 studies which examined the effect of HIIT on physical function (Table 4). One used the short physical performance battery (SPPB), six used gait speed or the 6 minute walk test (6MWT), nine used the timed up and go (TUG) test, and one used the 400 m walk test (some studies utilized more than one outcome). Of the 12 studies examining physical performance, all reported ≥1 parameter was improved by HIIT. The only study examining SPPB reported HIIT improved SPPB performance.

*****INSERT TABLE 4 ABOUT HERE****

Table 3. Summary of study details concerning HIIT and physical performance.

4 Discussion

This scoping review provided an overview of existing literature pertaining to HIIT and sarcopenia outcomes. We examined outcomes according to the revised EWGSOP definition [1] to facilitate translation of research findings into clinical practice. Firstly, the earliest article cited was Adamson et al. [31] published in 2014, which speaks to this rapidly emerging area of research. This review catalogues existing literature, with a view to facilitating discussion of research opportunities and issues that need to be addressed in future studies.

In relation to our second objective, training programmes ranged in duration from 2-24 weeks (median = 9.5 weeks), incorporated resistance training based HIIT, running/walking HIIT, cycling HIIT, and HIIT combined with other exercise modes (i.e. resistance training). Populations studied were commonly in the 7th decade of life, and mostly living independently. In relation to our third objective, muscle quantity or quality was most frequently studied in the included literature. DEXA was the most utilized measurement method, which is in line with the EWGSOP algorithm for sarcopenia case findings in clinical practice [1]. However, these are only routinely found in research facilities and hospitals and would likely require a referral from primary care before an individual received a DEXA scan. Importantly, none of the included studies involved participants who had been diagnosed with sarcopenia using a formalized definition. This limits the clinical significance of the included literature and clearly highlights a need for further work in this population.

294

295 **4.1 HIIT and muscle function**

296 According to the revised EWGSOP definition of sarcopenia [1], muscle function is primarily
297 considered as muscle strength. Yet, the chair stand test (or its variations) is named as a parameter that
298 measures muscle strength. However, as the chair stand test relies on the ability to generate force over
299 a short period of time, this could be considered a test of muscle power, rather than a measure of
300 maximal force. The term *dynapenia* (i.e. the age-associated reduction in muscle strength and power
301 [60,61]) was originally used to differentiate itself from sarcopenia [62], which has its roots in age-
302 related reduced muscle mass (Greek translation = 'poverty of flesh' [63]). However, more recent
303 definitions and diagnoses of sarcopenia have broadened to include muscle function. In this context,
304 when one measures muscle strength using non-isometric movements (i.e. when work occurs), force,
305 distance, and time can be extracted, which is quantification of power. Thus, we believed it pertinent
306 to include studies which concerned muscle power within this review. In fact, muscle power
307 associates more strongly with physical performance and independence than muscle quantity [64,65],
308 which may explain why the chair stand test is at the forefront of the revised EWGSOP algorithm for
309 diagnosing and quantifying sarcopenia [1]. Moreover, as this is a scoping review, our *a priori* aim
310 was to outline the range and characteristics of outcome variables examined.

311 In this review, only four studies used grip strength as an outcome measure [35,36,48,50]. This is
312 interesting to note as EWGSOP propose grip strength as the primary measurement of muscle strength
313 in clinical practice and research studies [1]. However, of these four investigations, one was published
314 before the revised EWGSOP guidelines, and three were published the same year, so data collection
315 may have been pre-update. Wiśniowska-Szurlej et al. [66] examined handgrip strength and other
316 mobility parameters including gait speed, balance, and chair stand and observed weak correlations
317 between handgrip strength and mobility in older adults under long-term care facilities. Yee et al.
318 (2021) corroborated this finding reporting weak correlations between chair stand test and handgrip
319 strength in community-dwelling older adults. Similarly, changes in handgrip strength do correlate
320 with changes in leg muscle strength of physical performance during an exercise intervention program
321 in frail older people [68], suggesting it is not a good surrogate of mobility, muscle function, or
322 change in muscle function of muscle other than those involved in gripping. If the two proposed
323 measures of muscle strength to diagnose sarcopenia are not in agreement, then an alternative method
324 for measuring muscle strength is necessary in this population. This may explain why most studies in

this review have not measured handgrip and instead opted for isokinetic dynamometry, considered the gold standard for assessing muscle strength but not commonly used in a clinical setting. When considering the body of studies examining muscle function, the majority report increased strength (70% of studies) or power (100% of studies) following HIIT.

Considering reduced muscle function is at the forefront of the recent update on the definition and treatment of sarcopenia [1], any intervention targeting the prevention or reversal of sarcopenia must be capable of enhancing muscle strength. To our knowledge, Losa-Reyna et al. (2019) is the only investigation to examine an exercise intervention containing HIIT in frail older adults. These authors examined the influence of a 6-week multicomponent exercise intervention (including walking-based HIIT) focused on enhancing muscle power in ~84-year olds (range 77-96 years; 75% females; 35% pre-frail and 65% frail). Post-intervention, leg press strength had improved by 34%, and muscle power improved by 47%. Moreover, load at peak power on the force-velocity curve increased by 23%, which suggests this type of intervention may improve muscle strength and power in frail and pre-frail elderly.

4.2 HIIT and muscle quantity or quality

In this review, 20/21 (95%) of studies report appendicular skeletal muscle mass measured by DEXA, BIA, or MRI, or cross-sectional area of the thigh by MRI or pQCT scan, which are the primary measurement of muscle quantity proposed by EWGSOP in clinical practice and research [1]. The remaining investigation used air plethysmography to determine whole body lean mass [43]. When considering the body of studies examining total body lean mass, several reported no increase from pre-HIIT [8,34,36,37,39,43,45,47,48,55,57,59], whereas some reported an increase post-HIIT compared to pre-HIIT [40,51,52]. To add further uncertainty, two studies which observed no increase in whole body lean quantity observed increased thigh lean mass [45,46]. Taken together, it is unclear whether HIIT can significantly increase muscle quantity or quality, and the result may be determined by measurement technique of muscle quantity.

There are no data concerning the effect of HIIT on skeletal muscle quantity or its surrogates (e.g. fat free mass [FFM], lean body mass) in adults diagnosed with sarcopenia, or oldest old humans, despite emerging evidence in the rodent model [69]. Thus, data from the middle old and young old must be extrapolated until these studies exist. In this context, and despite no changes in muscle strength,

Robinson et al. (2017) observed a ~1 kg increase in FFM in sedentary ~71 year olds following 3 days/week cycling HIIT and 2 days/week of treadmill walking. This increase was greater in a resistance training only group, however. Interestingly, FFM was also increased to the same extend in a young (~25 years old) sedentary cohort, suggesting HIIT can increase FFM in the young and old to equal magnitude. This can be interpreted in two ways: 1) sedentary older adults maintain muscle plasticity and sensitivity to HIIT into older age, and 2) HIIT can increase FFM quantity in young sedentary adults who have not experienced muscle wastage. However, as all participants were untrained, increased FFM could be attributed to both young and old participants being HIIT-naïve.

It would have been a reasonable *a priori* hypothesis to predict HIIT performed at the greatest relative intensity (i.e. all-out or SIT) would result in the greatest increases in muscle quantity, as intensities closer to maximal voluntary contraction are known to induce muscle hypertrophy [70,71] . However, this was not observed as Aboarrage Junior et al. (2018) utilized an all-out protocol, with no reported increases in lean mass. Likewise, it may have been expected untrained participants would exhibit the greatest increase in muscle quantity. However, Herbert et al. (2017) examined the body composition changes in a group of previously sedentary older males and masters athletes, and reported FFM increased ~3% (from ~67 kg to ~69 kg) and ~4% (from ~65 kg to ~68 kg), respectively. This suggests HIIT may be efficacious at increasing FFM in highly active older males and previously sedentary older male, if they are HIIT-naïve. Yet, these data are not ubiquitous through the included literature of this review. Adequate intake of dietary protein is also an important consideration for older adults and any potential exercise induced increases in muscle mass are likely to be influenced by this [72].

4.3 HIIT and physical performance

In this review, all of the studies assessing physical performance reported gait speed (part of the SPPB), the SPPB, or the TUG test as an outcome, which are the primary measurements of physical performance proposed by EWGSOP in clinical practice and research [1]. Four investigations also reported the 5 repetitions chair stand test separately [30,31,39,42]. However, this is one element of the SPPB, so those reporting SPPB values will have conducted this test. When considering the body of literature examining physical performance, all studies reported improvements post-HIIT. When considering studies examining physical performance, all studies report increased physical

385 performance of ≥1 parameter following HIIT. In some instances HIIT did not improve performance
386 more than another training method, where investigations had a parallel arm [32,38,39]. Physical
387 performance represents a multidimensional construct involving a range of physiological systems
388 across the whole-body [72] and is a key component in the definition of severe sarcopenia [1].

389 Losa-Reyna et al. (2019) observed that a 6-week multicomponent exercise intervention (including
390 walking-based HIIT) focused on enhancing muscle power improved the frailty phenotype by 1.6
391 points, muscle strength by 34%, and muscle power by 47%, suggesting this type of intervention is
392 feasible in frail and pre-frail elderly. As this intervention was multicomponent, it is not possible to
393 quantify the contribution of HIIT to the overall improvement, and therefore it is difficult to ascertain
394 whether adaptations would have occurred were HIIT examined in isolation, rather than
395 simultaneously with a resistance training programme.

396

397 **4.4 Strengths and limitations**

398 In cataloguing the research concerning HIIT and sarcopenia, several issues and considerations came
399 to light, all of which have important implications for the interpretation of this body of literature, and
400 improvement of future investigations. Firstly, the use of exercise terminology requires clarity. In this
401 context, we mean the definition of 'HIIT'. HIIT has previously been described as periods of work
402 >85% VO_{2peak} or 85% HR_{max} or equivalent perception-based approaches, interspersed by recovery
403 periods [73]. Only articles matching this description were included in this article. Several articles
404 were returned from our database searching which termed the exercise intervention HIIT, but often
405 these did not reach this threshold of intensity. Similarly, when exercise is described as 'all-out', this
406 should be termed SIT, which although a subcategory of HIIT, is unique in its prescription [74]. It is
407 imperative to classify protocols based on the nature of exercise prescription as different interval
408 exercise classifications will alter experience and potentially subsequent adaptation to the exercise
409 [75]. The major limitation of the present scoping review is the lack of studies in older adults
410 diagnosed with sarcopenia. Whilst the literature assessment was comprehensive, it is possible that
411 studies may have been missed from the analysis, but as three databases were searched, it is unlikely
412 enough were missed to create a large void in the included literature.

413

4.5 Recommendations for advancement of the investigative area

In relation to our fourth objective (provide recommendations for the advancement of the investigative area), this review revealed a dearth of studies considering participants diagnosed with sarcopenia. Therefore, our primary recommendation for advancement of the research area is to increase studies that recruit participants or patients with sarcopenia, or those who are at risk from sarcopenia (i.e. the oldest old). Secondly, given the issue regarding terminology and exercise intensity discussed above, authors are encouraged to be consistent in the use of exercise terminology by adhering to the consensus on exercise reporting template (CERT; [76]) in future investigations, which would permit assessment of intervention heterogeneity. Thirdly, studies included within this review had a sample size ranging from 8-82 participants, possibly due to resource commitments associated with having large sample sizes and/or rigorous research design. We suggest multicentre RCTs to improve a) statistical power, and b) the quality of available evidence, as only 17/32 studies achieved ≥5 on the PEDro scale. Finally, although this review focused directly on sarcopenia outcomes (i.e. quantitative assessment), qualitative investigations on the perceptions of adults with sarcopenia on this type of exercise and how it could be delivered to this population with minimizing any barriers will be beneficial for the field of gerontology.

4.6 Conclusions and practical recommendations

In conclusion, most studies presented herein utilized outcome measures defined by the revised EWGSOP guidelines. There was divergence observed in exercise interventions, with HIIT interventions involving a range of exercise modes delivered in a range of settings. Currently, there is some evidence suggesting HIIT may improve outcomes relating to sarcopenia. However, there are few studies investigating any form of HIIT in the very old, or those diagnosed with sarcopenia. Therefore, more intervention studies are needed in this population to confirm this phenomenon and confidently quantify the effectiveness of HIIT. In addition, we need to understand if this is a safe and feasible training approach in this population. In a practical context, combined interventions involving HIIT and resistance training are a worthy avenue for investigation as resistance training is the most potent stimulus to increase muscle quantity and studies herein showed divergent results concerning HIIT and muscle quantity. Finally, HIIT or SIT that is easy to apply (i.e. without equipment needs, travel, specialist training, and intensity monitoring such as heart rate or power output) or can be

supported virtually is likely needed to promote the transition of HIIT from the laboratory to the real world.

5 Author contributions according to the CRediT taxonomy

Conceptualization: Lawrence D Hayes, Christopher Hurst; Methodology: Lawrence D Hayes, Christopher Hurst; Formal analysis and investigation: Lawrence D Hayes, Nilihan EM Sanal; Investigation: Lawrence D Hayes, Christopher Hurst; Writing - original draft preparation: Lawrence D Hayes, Bradley T Elliott, Zerbu Yasar, Theodoros M Bampouras, Nicholas F Sculthorpe, Nilihan EM Sanal, Christopher Hurst; Writing - review and editing: Lawrence D Hayes, Bradley T Elliott, Theodoros M Bampouras, Nicholas F Sculthorpe, Nilihan EM Sanal, Christopher Hurst; Visualization: Bradley T Elliott; Project administration: Lawrence D Hayes, Christopher Hurst; Funding acquisition: N/A

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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