THE UNIVERSITY OF HULL

Individualisation of Physical Activity Measurement Using Wearable Technology

being a thesis submitted for the Degree of Doctor of Philosophy at the University of Hull

By

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July 2023

Abstract

The benefits of performing regular physical activity are well documented for reducing the risk of comorbidities such as cardiovascular disease. Physical activity intensity is an important component associated with such benefits, with National Health Services advocating for moderate intensity as the minimum requirement to meet physical activity targets. For many years moderate physical activity intensity has been objectively quantified using absolute measures of physical activity intensity, with the most popular being metabolic equivalents (METs). Although the MET provides an objective measure of intensity, it does not account well for inter-individual differences in cardiorespiratory fitness. In contrast, relative measures of physical activity such as % heart rate reserve (HRR) account much better for inter-individual cardiorespiratory fitness. However, the primary limitation in using relative measures of physical activity intensity to date has been the ability to use these measures at a population level.

One solution for using relative measures at a population level is wearable technology. Sales of wearable devices are growing rapidly, with the most popular wearable device being the smart watch, and the most popular smart watch being the Apple Watch. The Apple Watch has the capacity to measure heart rate using plethysmography (PPG) sensors when placed on the wrist. Wearable devices now have the capability to measure heart rate with good accuracy, especially at rest, low, and moderate intensity. Thus, relative measures of physical activity monitoring and prescription are now becoming widely available to the general population. Therefore, the aims of this thesis were to (1) examine the agreement and relationship between %HRR and METs, (2) examine how well %HRR as measured by the Apple Watch compares to criterion intensity (VO_2R) and the native Apple Watch Activity app

for measuring moderate intensity while walking, (3) examine the plausibility of guiding walking cadence to meet relative moderate intensity via metronome and haptic feedback from the Apple Watch, (4) examine the perceptions of participants surrounding the use and knowledge of moderate intensity and physical activity guidelines, and (5) examine the perceptions of participants on wearable technology.

The first study (Chapter 4), a systematic review with meta regression sought to assess the agreement or disagreement between absolute and relative intensity measures of physical activity. A total of 15 papers were incorporated in the systematic review, where a comparison between METs and relative values (%HRR, $\%HR_{max}$, $\%VO_2R$, $\%VO_{2max}$, HR_{index}) of intensity was undertaken. The results identified agreement for how intensity was classified (i.e., light, moderate, or vigorous) between relative and absolute intensity values in 60% of the trials. Raw data was obtained from three authors incorporating 3 studies and 290 participants. A Bayesian random intercept logistic regression was conducted to examine the agreement between relative and absolute intensity, showing agreement in 43% of all trials. Two studies had identical relative variables totalling 240 participants included in the random intercept regression. The best performing model was a log-log regression which showed that for every 1% increase in METs, %HRR increased by 1.12% (95% CI: 1.10–1.14). Specifically, the model predicts at 3 METs (lower bound of moderate intensity), %HRR was estimated to be 33% (95% CI: 18–57), highlighting the discrepancies between absolute and relative measures of physical activity intensity.

The main aim of the first experimental study (Chapter 5) was to compare a newly developed Apple Watch app (MVPA app) using %HRR as a measure of moderate-to-vigorous physical activity (MVPA) compared to the native Apple Watch Activity app (the green ‘exercise’ ring). The purpose of the investigation was to determine how accurately each method measures moderate intensity walking against the criterion measure of intensity, %VO_2R. There were also several secondary aims, including obtaining the required walking cadence to reach criterion moderate intensity, 40% VO_2R, comparing the Apple Watch’s ability to measure resting heart rate compared to a criterion laboratory measure and examining subjective measures (RPE, thermal sensation, breathlessness, and the talk test) ability to estimate moderate intensity. Bayesian posterior distributions indicated that at the inflection point (the treadmill speed at which the Apple Watch green ring advanced), the native Apple Watch app mean was 33% VO_2R (CI: 31% to 36%) the MVPA app was 43% VO_2R (95% CI: 40% to 44%). A Bayesian regression model identified %HRR and walking cadence estimated by the Apple Watch best described by a non-linear smooth regression, predicted that a mean walking cadence of ~123 steps·min^{-1} was required to reach 40% HRR. Mean (SD) cadence at 3 METs was 104 (9) steps·min^{-1}. Bayesian regression models identified the subjective measures to be poor indicators of moderate intensity. At an RPE of 3 (moderate) the %HRR point estimate was 41% (95% CI: 23 – 57). Thermal sensation at 8 (slightly warm) was 39% HRR (95% CI: 22% - 58) and breathlessness of 3 (moderate) was 42% HRR (95% CI: 25 – 60). The uncertainty in subjective measures is highlighted by the large credible intervals spanning at least two intensity classifications.

The main aim of the second experimental study (Chapter 6) was to examine the use of cadence cues to guide walking intensity to criterion moderate intensity (40% HRR) via the Apple Watch using metronome and haptic cues. These trials were compared to a self-paced condition whereby participants were instructed, via NHS guidelines to moderate intensity, to walk at a cadence they perceived to be moderate based on the intrinsic, subjective instruction advised from NHS guidelines. Synchronisation between foot contact and the metronome cue were observed in a subsample of 30 participants, with the criteria for synchronisation being if foot contact was made within -0.1 to 0.1 seconds of the metronome cue. Results indicated that the metronome cue guided 81% of participants to criterion moderate intensity, whereas haptic cues guided 68% of participants to criterion moderate intensity. In the self-paced trials, 50% of participants walked at a cadence high enough to elicit criterion moderate intensity. Synchronisation with the metronome cue in the subsample of participants was achieved in 43% of foot contacts. The Bayesian posterior distributions identified participants ability to match their cadence tempo with the metronome cue tempo to be poor, with the mean effect (95% CI) being 138 (CI: 136 to 140) beats·min^{-1}, while cadence was 126 (124 to 129) steps·min^{-1}. Similarly, the haptic cue was administered at a mean effect of 140 beats·min^{-1} (CI: 137 to 143) whereas cadence in the haptic cue trials was 122 (ci: 120 – 125) steps·min^{-1}.

The first qualitative study (Chapter 7) gathered insights into participants’ perceptions of NHS physical activity guidelines. A subsample of 23 participants who had participated in the laboratory trials agreed to partake in semi-structured interviews. A semi structured interview guide covering questions related to NHS physical activity guidelines, physical activity intensity and perceptions of wearable technology aiding physical activity was developed, with interviews conducted following the completion of each participants’ laboratory trial. Five main themes arose from the data. Collectively, the themes indicate that it is likely a large percentage of the population do not understand government guidelines for moderate intensity physical activity and are unaware of how moderate intensity should make them feel when being performed. Additionally, only three participants correctly identified the cardiovascular component of ‘150 minutes of moderate intensity or 75 minutes of vigorous physical activity a week’ described in UK NHS guidelines for physical activity. To generalise, peoples’ understanding of physical activity guidelines is poor.

Finally, the second qualitative study (Chapter 8) identified perceptions of wearable technology and the application of nudge theory to guide physical activity intensity, based on the trials performed in Chapter 6. Semi-structured interviews were conducted with the same group of 23 participants. The results indicated that participants in general would be open to the use of nudge theory to promote physical activity if it was of benefit to their cardiovascular health. The use of a metronome as a cadence cue was met with some conflicting opinions. If used persistently to guide walking cadence several participants highlighted it may be irritating to the user. Additionally, a large proportion of participants found the haptic cue to be too weak to feel during arm swing, which is a limitation that wearable device manufacturers may wish to address if they were to use haptic cues to guide physical activity intensity.

The findings from this thesis provide evidence for the benefits of relative intensity when monitoring and prescribing physical activity intensity. Moreover, these benefits are now widely available at a population level through wearable devices. The results identify the large discrepancies between relative and absolute intensity and as such, relative measures offer a more accurate method of monitoring physical activity at both an individual and, now arguably, at a population level. Furthermore, it is evident people do not understand National Health Service guidelines for physical activity. Collectively these findings have important implications for physical activity practitioners, health professionals, and researchers who seek to enhance physical activity outcomes at a population level.

Acknowledgements

This doctoral thesis would not have been possible without the generous support of numerous people both from my professional and personal life. First, I would like to thank my supervisors Prof. Grant Abt, Prof. Natalie Vanicek, Prof Amanda Benson and Prof. Tony Myers, they have supported, challenged, and offered an abundance of expertise that have made this process over the past four and a half years invaluable. I would also like to thank the wider Sport, Health and Exercise Science team who have offered their support throughout this process through conversations, laboratory support and participation in laboratory trials at a moment's notice. A special mention to the laboratory technicians for their support, Tom Nickolay and James Metcalfe, not only have they supported laboratory sessions, but their discussions and persistent questioning have been more helpful than they may know.

Personally, I would like to thank my partner Paige Wood who has supported me throughout this process with love and encouragement and has dutifully taken on the role of rant listener with careful kindness. Without your love and support this would not have been possible. I also owe a huge thank you to a mother bear for 'putting up' with me during my time at the University of Hull and offering an unlimited supply of coffee and 'œufs.'

Finally, a special mention must be made to my Mum and Dad who have supported and encouraged me throughout my life to chase goals and dreams, without your support this would not have been possible.

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1. Introduction

The benefits of physical activity for reducing the risk of developing comorbidities such as cardiovascular disease (CVD) and obesity-related illness are well documented (Stamatakis et al., 2018; Zaccardi et al., 2019). (For the purpose of this thesis physical activity and exercise will be used interchangeably. Exercise refers to a subset of physical activity that is planned, structured, and has an immediate objective. Physical activity refers to activity that can be accumulated throughout daily living). Governments around the world are also aware of the associated benefits of physical activity, both for improving quality of life, but also the down-stream impact this can have on the wider economy (Hafner et al., 2019; 2020). This recognition has been supported by several publications developed by professional associations including the ACSM that set guidance on the minimum physical activity required to ensure health-related benefits (Liguori, 2022).

Current UK government guidelines recommend that to be physically active, a person must complete a minimum of 150 minutes of moderate aerobic physical activity (MPA), or 75 minutes of vigorous aerobic physical activity (VPA) per week (NHS guidelines, 2018). However, in England alone, an estimated 3 million middle-aged (35 – 55 years old) adults currently do not meet these guidelines (OHID, 2023) There are many factors that influence whether people meet these physical activity recommendations, including self-perceived lack of time, the ability to self-motivate and the perceived unpleasantness of physical activity (Ebben and Brudzynski, 2008; Lovell, El Ansari and Parker, 2010). However, identifying barriers to participation in physical activity may be oversimplifying the problem. Psycho-social barriers such as self-efficacy, environmental and socioeconomic inequalities may create a wider issue impacting physical inactivity (Xiao et al., 2019), as well as other factors such as the wider public's understanding of physical activity recommendations and knowledge of health promotions (Knox et al., 2015; Vaara et al., 2019). Understanding the necessary physical activity volume and intensity required to meet government guidelines is important for the general population to understand to promote better health. Concerningly, it would seem very few people have a general understanding of this. Vaara et al. (2019) reported that of 776 young Finnish men (26 (7) years old), who were invited to the Finnish military refresher training, only 40% reported being aware of physical activity recommendations. Moreover, only 4% correctly identified both aerobic and resistance training recommendations, and only 7% correctly identified the recommendations for aerobic physical activity. Additionally, there was a significant correlation between those participants who had no awareness of physical activity guidelines and lower cardiorespiratory fitness (CRF) and muscular fitness.

Although awareness and understanding of government physical activity guidelines is important, a person's ability to self-report physical activity also plays a key role in measuring and subsequently performing adequate physical activity volume and intensity. Colley, Butler, Garriguet, Prince, & Roberts, (2018) compared self-reported physical activity using the Canadian Health Measures Survey, against an accelerometer worn over the right hip, in 2,372 Canadian adults. They found that participants self-reported a mean of 49 minutes of moderate or vigorous physical activity (MVPA) per day compared to accelerometer data which measured a mean of 26 minutes MVPA per day. This is a substantial difference between objectively measured and subjectively measured physical activity, and one that highlights the participants' lack of ability to assess both intensity and duration of physical activity accurately through subjective feeling. One specific problem with self-reporting physical activity is understanding the intrinsic feeling a person experiences during moderate intensity physical activity. The UK, NHS guidelines suggest MPA "should raise your heart rate, make you feel warmer and breathe faster" (nhs.uk, 2022). These guidelines are very subjective and often difficult to interpret and recall (Knox et al., 2013; 2015; Piercy et al., 2020). Knox et al. (2013) study indicated, from survey data only 18% of 1797 UK adults were able to correctly recall current UK guidelines to physical activity. Additionally, Piercy et al. (2020), again from survey data found that only 2% of physical activity contemplators (those who report performing infrequent physical activity) were aware of the government guidelines to physical activity in the United States. A potential reason for this misinterpretation might be that physical activity guidelines are not necessarily intended for public consumption (Latimer, Brawley and Bassett, 2010), but are aimed at 'professionals, practitioners, and policymakers (UK CMO, 2019). Previous research suggests that not meeting the physical activity guidelines is a complex problem that is multifactorial in nature.

One method that may resolve a number of these issues involves the use of wearable technology to guide physical activity monitoring and prescription. Sales of wearable technology products have grown considerably in recent years (Peake, Kerr and Sullivan, 2018; Phillips et al., 2018). For example, worldwide sales of smart watches (e.g., Apple Watch, Fitbit x) are set to reach 53.6 billion dollars by 2025 (Statista, 2023b). In 2020, there were over 100 million Apple watch users worldwide (Statista, 2022a). To counter the issue of subjective self-reporting of physical activity intensity, a high proportion of wearable devices can now measure heart rate, thus allowing for objective, relative intensity physical activity prescription and monitoring to reach a mass audience. Measures of relative intensity take into account both the minimum and maximum capacity of the individual (Siddique et al., 2020). Measuring relative intensity allows for a more individualised and thus a more accurate inter-individual monitoring, recording and prescription of physical activity intensity (Amorim et al., 2017; Kujala et al., 2017; Serrano et al., 2017). For example, a heart rate of 130 beats·min^{-1} contains no contextual information about the CRF of the person and therefore it is impossible to know if that heart rate represents 'moderate' intensity. In contrast, if using a relative measure of intensity such as % heart rate reserve (%HRR), then the exercising heart rate can be expressed relative to that person's resting and maximal heart rates, to provide a more accurate representation of the intensity relative to their CRF (assuming resting heart rate decreases with increasing CRF (Jensen et al., 2012; Kang, Ha and Ko, 2017)).

Individualisation is the process of using a person's own data to make physical activity prescription more accurate in terms of their CRF capacity. Large inter-individual variability in cardiorespiratory responses to standardised physical activity exists (chapter 4). This variation to the same absolute external physical activity intensity can often vary substantially, from high relative intensity to low relative intensity depending on CRF (Lehtonen et al., 2022; chapter 4). The ability to individualise physical activity monitoring and prescription on a population-scale has been somewhat limited in the past, and in many ways is still limited today. Traditional wearable devices, such as the pedometer and accelerometer, monitor step counts whereby individual step rates and total step accumulation are recorded. The issue with this method of physical activity monitoring is that it cannot accurately identify individualised relative intensity thresholds, as no relative measure of intensity is being monitored, e.g., heart rate, and thus only has the capacity to measure absolute intensity i.e., the energy required to perform an activity (Siddique et al., 2020) is monitored. The most common absolute intensity variable is the MET. A MET is defined as a ratio of the metabolic cost induced by different types of physical activity and intensity compared to the metabolic cost of sitting quietly (Byrne et al., 2005) and is generally set as equivalent to 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ oxygen consumption. The MET has become a popular measure of physical activity intensity among researchers and health and fitness professionals due to its ability to prescribe physical activity intensity across a spectrum of activities, and to a wide range of the population. The ACSM reports 3 METs is equivalent to MPA (Liguori, 2022). However, METs are a standardised measure across the population, and do not consider individuals' CRF. Therefore, the accuracy of such measures is questionable (Byrne et al., 2005; Iannetta et al., 2021). For example, a range of values have been reported for resting oxygen consumption when measured directly under laboratory conditions - 3.4 (0.6), 2.4 (0.5), 4.3 (0.9), 2.9 (0.4), 3.0 (0.4) (range 2.0 to 3.8) (Lounana et al., 2007; Cunha et al., 2010; Sergi et al., 2010; Miller et al., 2012; Abt, Bray and Benson, 2018). These studies clearly show there is considerable variation from the standard value of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$, which will have an impact on the monitoring of MVPA.

More traditional relative measures of intensity such as a heart rate chest strap have been available to the general public for well over 30 years (Kite-Powell, 2022). However, although they are useful for athletes and coaches who want to track intensity during training sessions, their useability for the general population is questionable, due to the requirement for positioning a chest strap heart rate monitoring device. As many wearable technology devices now have embedded photoplethysmography (PPG) sensors, monitoring heart rate has become accessible to the public. Having contemporary devices that seamlessly integrate physical activity prescription and monitoring into fashion, clothing and general lifestyle could play a key factor in increasing physical activity adherence. One contributing factor to the high rate of physical inactivity could be people's lack of ability to identify MPA accurately, the minimum required intensity prescribed by government guidance to improve CRF or reduce morbidity/ mortality risk (nhs.uk, 2022). Advancements in wearable devices have developed sufficiently to be able to solve this problem and offer a valid and reliable method of monitoring physical activity, especially at moderate intensity (Khushhal et al., 2017; Abt, Bray and Benson, 2018). Additionally, modern wearable devices could promote physical activity and behaviour. As the device is in close proximity to the user, it has the capacity to nudge the wearer effectively and potentially improve physical activity outcomes (Yen and Huang, 2021). For example, nudges can be designed to increase physical activity, calorie expenditure and reduce sedentary behaviour. Modern devices also have a large touch screen, and provide quick and easy access to personalised health data and self-tracking features that can be used to educate users and potentially improve self-efficacy (Rieder et al., 2021).

To maximise health benefits at the population level, the ability to scale interventions is key. In terms of physical activity mode, walking is the most popular form of physical activity with 70% of UK adults walking at least once a week (Sport England, 2020). Walking is not only performed as physical activity but often used for transportation, occupation and in domestic duties. Given that heart rate measured using PPG is very accurate at low and moderate intensity (Wallen et al., 2016; Khushhal et al., 2017; Abt, Bray and Benson, 2018), the combination of PPG-derived heart rate and walking might represent the optimal combination to reach people at scale. Because of its popularity, previous research has also tried to identify a walking cadence that will elicit moderate intensity. Several studies have advocated that a walking cadence of 100 steps·min^{-1} adequately meets the 3 METs threshold for moderate intensity (Tudor-Locke *et al*., 2018, Marshall *et al*., 2009, Nielsen *et al*., 2011, Abel *et al*., 2011). However, more recent studies have examined the legitimacy of this 'one size fits all' approach to walking intensity thresholds (O'Brien et al., 2018; Abt et al., 2019). New evidence has highlighted several fundamental flaws with the absolute intensity approach to walking prescription. For example, evidence suggests there are a number of physiological and biomechanical factors that hinder the accuracy of 100 steps.min^{-1} as an absolute approach to MPA, most importantly, differences in CRF (Abt et al., 2019), but also leg length/height, BMI, age, and sex all impact the walking cadence required to meet moderate intensity (Ayabe et al., 2011; Rowe et al., 2011; Peacock et al., 2014).

The current body of evidence has highlighted several key factors that may be causing physical activity prescription and monitoring to be inaccurate. A need for personalised physical activity monitoring and prescription exists, and developments in wearable devices now offer the opportunity to advance more accurate means of tracking, and thereby prescribing physical activity on an inter-individual basis. A greater understanding of how physical activity guidelines are interpreted may also help develop better physical activity guidance and literature to aid those who do not wish to wear a wearable device. The ability to interpret subjective feelings when exercising more accurately at prescribed intensity thresholds would be beneficial in promoting more accurate intensity physical activity.

Therefore, the general aim of this thesis is to investigate the use of wearable technology for monitoring relative intensity to ensure people complete individualised, moderate relative intensity physical activity.

1.1 Specific Aims

The thesis has the following specific aims:

1. To examine the agreement and relationship between %HRR and METs.
2. To examine how well %HRR as measured by the Apple Watch compares to criterion intensity (VO2R) and the native Apple Watch Activity app for measuring moderate intensity while walking.
3. To examine the plausibility of guiding walking cadence to meet relative moderate intensity via metronome and haptic feedback from the Apple Watch.
4. To examine the perceptions of participants surrounding the use and knowledge of moderate intensity and physical activity guidelines.
5. To examine the perceptions of participants on wearable technology.

2. Literature Review

Obtaining the highest attainable standard of health and thus improving life expectancy is a key principle highlighted in the World Health Organization's (WHO) constitution (who.int, 2023). WHO defines health as a 'state of complete physical, mental and social well-being and not merely the absence of disease or infirmity' (who.int, 2023). A number of factors may impact this goal, including; genetics, behaviour, environmental and physical influences, medical care and social factors (CDC.gov, 2019). A number of factors influence social determinants of health such as social conditions that influence the health of people and communities (Marmot, 2000). Often shaped by socioeconomic position and political factors such as societal values, culture, and policies. An individual's socioeconomic position can be shaped by various factors including education, occupation, and income (Marmot, 2000; Braveman and Gottlieb, 2014). ONS statistics indicate that 22.8% of total deaths in the UK were considered avoidable (ons.gov.uk, 2023). In this sense, 'avoidable' means deaths that were preventable with effective public health intervention or treatable with primary prevention interventions. Although there are multiple ways of avoiding, or in other words, preventing, certain morbidities, the current thesis focuses on one in particular - physical activity. In the UK, insufficient physical activity has been reported to be associated with 1 in 6 deaths, whilst up to 40% of variance of many long-term, preventable conditions such as type 2 diabetes, is explained by physical inactivity ("Physical activity," 2021). As such, physical activity may play a significant role in reducing preventable deaths.

Physical activity plays an integral role in contributing to health. Specifically cardiorespiratory fitness (CRF) and the prevention of cardiovascular disease (CVD) (Weintraub et al., 2011; Barengo et al., 2017; Argyridou et al., 2019) Preventing CVD is an important economical and health impact factor that requires attention from health professionals (Barengo et al., 2017; Argyridou et al., 2019; Collins et al., 2022). A recent model of potential CVD trends in the UK highlighted a possible economic cost of £54 billion over the next 10 years including health, social and informal care and quality adjusted life years if the recent slowing of CVD incidence were to persistently plateau (Collins et al., 2022). Additionally, other more developed countries are seeing similar concerning trends with the indirect cost of CVD in the USA set to reach $1 trillion by 2030, over double the cost compared to 2010 (Weintraub et al., 2011). Accordingly, interventions that reduce the prevalence of CVD, and other co-morbidity risk whilst improving CRF are of value.

2.1 All-cause mortality and physical activity

There is strong evidence to suggest CRF is inversely associated with all-cause mortality (Blair et al., 1989; Nocon et al., 2008; Kokkinos et al., 2022). A systematic review (Nocon et al., 2008) including 33 studies totalling 883,372 participants with an age range of 25 – 84 and follow up ranging from 4 to over 20 years, reported physical activity was associated with a 35% reduction in cardiovascular mortality, while all-cause mortality was reduced by 35%. Interestingly, studies that used a questionnaire (24) to assess PA reported lower risk reductions than studies that used more objective measures of fitness including fitness tests. Although the overall pooled risk reduction was reported at 35%, studies that objectively measured physical activity reported a risk reduction of 57% compared to a 30% reduction for studies using self-reported physical activity. Although the data may be compromised by the lower number of studies using objectively measured activity, the results align with other findings that suggest the accuracy of questionnaires is poor compared to objectively measured physical activity (Colley et al., 2018). Additionally, a recent epidemiological investigation evaluated the association of CRF and mortality risk for different races, sexes and age (Kokkinos et al., 2022) in a total of 750,302 U.S. veterans. CRF was objectively measured from a standardised treadmill test, from which peak MET levels were calculated. Results suggested that CRF and mortality were inversely related, independent of age, race, and sex. The lowest mortality risk was observed at approximately 14 METs, for both men and women and extreme cardiorespiratory fitness was not an indicator of increased mortality risk.

The importance of physical activity in improving CRF would therefore seem critical in prolonging quality of life and longevity. Although extreme levels of CRF have not been associated with an increased risk of mortality, theoretically there may be a 'sweet spot' whereby physical activity dose and relative risk of mortality plateau or become minimal in risk reduction. A study by Sabia et al., (2012) demonstrated that an accumulation effect might exist between physical activity and reduced risk of mortality. The data, derived from a longitudinal study of 10,308 civil servants aged 35 – 55 years old, reported that one hour of moderate intensity physical activity a week was associated with a 33% reduction in all-cause mortality. While the findings identify minimal amounts of physical activity to reduce mortality risk, of note is the questionnaire used to determine physical activity levels, of which accuracy has previously been discussed (Colley et al., 2018). However, additional evidence quantifies a dose-response relationship between physical activity and mortality risk in walking. For example, an accumulation of 4,400 steps·day^{-1} has been reported to reduce mortality rate by 41% and a steady decline in mortality rate was associated with more steps accrued up to a peak accumulation of 7,500 steps·day^{-1} in 17,708 older women (aged >72) (Lee et al., 2019). Additionally, a recent meta-analysis (Paluch et al., 2022) on a sample of

14,471 adults across 15 studies reported total daily steps reduced the risk of all-cause mortality in over 60s with increasing number of steps until a plateau occurred at approximately 6000 – 8000 steps$\cdot$day^{-1}.

2.2 Physical activity intensity

Although time spent performing physical activity is a contributing factor to CRF and mortality risk, optimising the time spent participating in physical activity via an increase in intensity may contribute to a higher CRF (Swain, 2005; Swain and Franklin, 2006) or a reduction in mortality risk (Swain and Franklin, 2006; Rankin et al., 2012). Current UK, USA, Canadian, Australian, and WHO guidelines place an emphasis on performing moderate or vigorous physical activity (Bull et al., 2020; Liguori, 2022; Brown et al., 2022; NHS.uk, 2022; Thomas et al., 2022). In all guidelines, the time spent exercising is reduced as the intensity increases. Specifically, each minute of vigorous intensity physical activity is counted as being equivalent to two minutes of moderate-intensity physical activity (nhs.uk, 2022). Evidence suggests that moderate intensity adequately stimulates the cardiorespiratory system to reduce mortality risk (Manson et al., 1999; 2002; Tanasescu et al., 2002). A prospective study by Manson et al. (1999) investigated moderate-intensity walking compared with vigorous-intensity walking in the prevention of coronary heart disease (CHD) in 72,488 female nurses aged 40 – 65 years old. Results indicated that every 5 MET-hours a week spent walking (approximately the equivalent of 1.5 hours of walking at a brisk pace per week) reduced relative risk of coronary events by 0.86 ([95%CI] 0.74 – 0.99) compared to vigorous exercise where there was not a greater magnitude of risk reduction for the equivalent of 5 MET-hours per week (0.92, [95%CI] 0.89 – 0.99). The authors highlighted that the study may have been impacted by the lack of participants performing vigorous physical activity, with only 26% of the cohort regularly engaged in vigorous physical activity on a weekly basis. Additionally, the results may contradict published findings from other large cohort studies, which have reported a greater coronary heart disease (CHD) risk reduction for vigorous intensity compared to moderate and light physical activity (Manson et al., 2002; Sesso et al., 2000; Tanasescu et al., 2002). Sesso et al. (2000) investigated the prevention of CHD in middle aged and older men (mean 57.7 years old, range 39-88), reporting that total physical activity levels >4200 $kJ \cdot wk^{-1}$ were associated with a 20% reduction in CHD. Additionally, vigorous physical activity was associated with a 10 – 20% reduced risk of CHD compared to moderate and light activity. Exercise intensity was classified in absolute terms as > 6 METs, while moderate intensity physical activity was classified as 4 – 6 METs. Although research has questioned the legitimacy of using METs to quantify exercise intensity (chapter 4) which will be discussed in detail within this chapter. Similarly in women, brisk walking or vigorous exercise of at least 2.5 hours per week reduced the risk of CVD by approximately 30% (Manson et al., 2002).

A review of epidemiological studies conducted by Swain and Franklin (2006) reported that five of the six studies included in the review, concluded that vigorous physical activity was associated with a reduced risk of CHD, but lower intensity physical activity was not (Lakka et al., 1994; Manson et al., 1999; Sesso, Paffenbarger and Lee, 2000; Tanasescu et al., 2002; Yu et al., 2003). However, total energy expenditure was not accounted for in any of those studies, and all studies used absolute intensity thresholds. Intensity was not classified on an individualised basis and authors reported intensity differed dependent on a person's fitness, motivation and interaction with peers and environment. Authors also reported that some activities classified as vigorous (> 6 METs) could have been performed at a moderate intensity, such as swimming and cycling. A more recent review also compared the cardioprotective benefits of vigorous- vs moderate-intensity physical activity, this time with total energy expenditure accounted for (Franklin, Kaminsky and Kokkinos, 2018). Authors concluded that vigorous intensity exercise provides greater cardiovascular benefits compared with moderate intensity physical activity. Vigorous intensity exercise was associated with a greater increase in CRF, especially for individuals with higher baseline CRF, which meant that for each 1 MET increase in CRF there was a 16% reduction in mortality. Additionally, vigorous intensity physical activity was associated with mechanistic benefits including, autonomic adaptations, specifically, decreased sympathetic outflow, increased vagal tone, increased, or maintained HR variability and endothelial function, decreased vascular stiffness, platelet adhesiveness, fibrinogen, and blood viscosity, increased diastolic filling time augmenting coronary flow and enhanced nitric oxide vasodilator function. Moreover, vigorous intensity is associated with a higher rate of carbohydrate oxidation which may benefit insulin sensitivity in obese individuals with and without diabetes mellitus (Kang et al., 1996).

2.3 Vigorous physical activity intensity

As such, vigorous physical activity seems to offer additional CRF benefits over moderate and light intensity. For these reasons, some researchers have advocated for high-intensity interval training (HIIT) as a method of improving CRF at a population level (Martin-Smith et al., 2020). HIIT is a form of exercise characterised by alternating periods of high or very-high intensity followed by lower-intensity periods (Ito, 2019). Although HIIT may be time effective and reap the additional CRF benefits associated with vigorous activity, there are concerns over long-term adherence, effectiveness, and enjoyment (Perri et al., 2002; Ekkekakis and Biddle, 2023). Ekkekakis and Biddle (2023) highlighted these concerns in a recent review of the literature. These authors reported that individuals assigned to vigorous-intensity exercise groups typically select lower intensities than that prescribed, and higher exercise intensity is associated with lower adherence and a higher drop-out rate. It was also reported that participants often disregarded the high exercise intensities prescribed and instead chose to exercise at a lower intensity, questioning the reliability of HIIT programmes. Additionally, a 6-month study comparing high and moderate exercise intensities (Perri et al., 2002) reported the higher intensity exercise group had lower adherence to the training programme compared to the moderate intensity group (58% vs 66%) and completed less weekly exercise (72 vs 85 min per week). That being said, if participants in the vigorous intensity group had been exercising at the correct intensity for 72 min per week, this would have been very close to the recommended 75 min per week advised by the NHS (nhs.uk, 2022) when compared to the moderate intensity group who completed 85 min per week, substantially under the 150 min per week advised in national guidelines. However, in the vigorous intensity group, adherence to the prescribed intensity was 71%, with 6% exceeding the target intensity, and 23% below the target intensity (65 – 75% HRR). In comparison, the moderate-intensity group achieved an 88% adherence to the target intensity (45 – 55% HRR) while 10% exceeded the target intensity, and only 2% fell below the target intensity. Additionally, there was a higher rate of injury in the high intensity training group (18.7% vs 8.3%), however Perri et al. (2002) speculated that the higher injury rate reported in the high intensity group, may have been due to subjective discomfort of activity, as opposed to actual injury. Regardless, a dropout rate of nearly 1 in 5 is alarming. Highlighting the relationship between high-intensity exercise, injury, and dropout, a recent meta-analysis of high intensity functional training (28 studies; 11,089 participants) reported an overall injury prevalence of 36% (95% CI 32 – 41%) and overall injury rate of 4.3 (95% CI 3.35 – 5.23) injuries per 1000 h of training (Knapik, 2022). This rate of injury for high-intensity exercise will clearly impact adherence. Cox et al. (2003) investigated exercise adherence in an 18-month intervention. Exercise intensity was prescribed at 45-55% HRR for moderate intensity and 65-80% HRR for vigorous intensity. Similarly, to Perri and colleagues, (2002), higher adherence was reported in the moderate intensity group (81%) compared to the vigorous intensity group (62%).

2.4 High Intensity Interval Training (HIIT)

It is worth noting that the studies highlighted above are a comparison of moderate and vigorous exercise intensity prescription. HIIT is often prescribed above the lower bound of vigorous intensity cut points (Liguori, 2022) and thus may further reduce adherence, the number of participants meeting the demands of the intensity prescribed, and enjoyment. Highlighting this, a non-randomised trial of community adults compared HIIT with standardised physical activity recommendations (150 min per week of moderate intensity exercise). After an initial demonstration of HIIT, 104 of 250 participants agreed to complete an unsupervised 12-month HIIT intervention, compared to 146 opting for the standardised physical activity recommendations (30 min, five times per week). Of the 104 participants who agreed to complete the HIIT programme, 102 completed the initial supervised session. However, during this session some individuals were unable to adequately meet the intensity demands of the prescribed exercise, with 86% of participants able to achieve 80% HR_{max} but just 40% able to achieve 90% HR_{max}. Although drop-out rate was 30% in the HIIT group and 33% in the moderate intensity group, the number of participants in the HIIT group fully adhering to two or more recorded HIIT sessions per week was only achieved by 23% of participants (Roy *et al.*, 2018). Although the study by Roy et al. (2018) was not randomised, their findings are also observed in RCTs with intervention arms of HIIT and moderate intensity. A number of RCTs have reported poor adherence to the intensity cut points required to meet criterion vigorous intensity and/or HIIT (Ekkekakis and Biddle, 2023). Regardless of monitoring techniques (RPE, % HRmax, % peak heart rate, VO_2peak) many studies have reported either poor adherence to intensity cut points (i.e., participants were unable to exercise at the prescribed intensity), or poor adherence to the prescribed high-intensity exercise duration (Conraads et al., 2015; Nytrøen et al., 2016; Stensvold et al., 2020; Taylor et al., 2020; Mueller et al., 2021). In a similar 12-month intervention study of HIIT vs moderate intensity physical activity (Jung et al., 2020), it was reported that participants who were instructed to complete three sessions a week of HIIT tended to favour completing moderate intensity physical activity. In the HIIT group, out of the three HIIT sessions prescribed per week, participants reported completing a mean (SD) of 1.9 (0.9) and 1.0 (0.9) sessions of HIIT at six and 12 months, respectively. Furthermore, those in the HIIT group increased moderate intensity sessions from a mean (SD) of 1.2 (1) to 1.4 (1.2) per week. In comparison, the moderate intensity group who were also prescribed three sessions per week, completed a mean (SD) of 3.8 (1.2) and 3.3 (1.3) sessions per week at six and 12 months, respectively. As a percentage change from baseline to 12 months, these figures represent a 67% reduction and a 10% increase in weekly sessions for the HIIT and moderate-intensity groups, respectively. The authors highlighted a potential limitation in monitoring high intensity exercise based on accelerometer data and using the Freedson et al. (1998) accelerometer cut points. The authors noted that “there is a lack of standardised methods to quantify HIIT based on accelerometery” (Jung et al., 2020, p. 3). Therefore, the true intensity that participants completed HIIT sessions is unclear. This provides further evidence for the need to individualise exercise prescription and monitoring using a relative measure such as % HRR, using such a method would’ve made the process of recording intensity during HIIT more reliable. While additional cardiorespiratory benefit may occur at higher exercise intensities, this bank of evidence suggests a favourable preference, adherence, and ability to reach target thresholds for moderate intensity physical activity. There may be several reasons for this, such as a preference for lower intensity exercise in populations that do not perform enough physical activity and there is clear evidence that adherence to high-intensity exercise is generally poor (Ekkekakis and Biddle, 2023; Ekkekakis et al., 2023). A fundamental objective of exercise prescription is to change personal behaviour to include physical activity into daily life. Arguably, the most impactful exercise prescription for individuals is one that is achievable and sustainable. As Kaminsky (2006) said:

'The art of exercise prescription is the successful integration of exercise science in behavioural techniques that result in long-term program compliance and attainment of the individuals' goals (Kaminsky, 2006 p. 136).

There is clearly a fine balancing act between duration, intensity, and frequency of physical activity for reducing mortality, co-morbidities and promoting CRF, while maintaining long term adherence to physical activity. One important issue that exercise scientists' have in providing clear instruction of frequency, intensity, and duration, is that government physical activity guidelines are often vague and can therefore be misinterpreted, (Knox et al., 2013; 2015; Prokop et al., 2014).

2.5 Physical activity monitoring and prescription

To gauge intensity more accurately an objective measure such as heart rate, oxygen consumption, or lactic acid production is required (Iannetta et al., 2020; Lehtonen et al., 2022). At a population level heart rate is currently the most feasible option for physical activity monitoring and prescription. Heart rate monitoring is widely accessible via wearable technology ("Apple watch users worldwide 2020 | Statista," n.d) with good validity, especially at moderate and low intensity (Khushhal et al., 2017; Abt, Bray and Benson, 2018). Although lactate and ventilatory thresholds may offer a more accurate, individualised physical activity intensity compared to using fixed percentage thresholds for classifying intensity (Weatherwax et al., 2019; Iannetta et al., 2020), their applicability in a real-world setting, at a population level is not feasible, at present. Lactate thresholds and ventilatory thresholds currently require expensive laboratory grade equipment, and a professional to conduct such testing and analysis. Additionally, wearable technology currently does not have the capacity to measure such physiological thresholds and thus heart rate, specifically %HRR, that takes into consideration an intensity range (HRrest to HRmax) that reflects both CRF fitness and physiological capacity may offer the most accurate relative measure currently available.

In a recent publication, Nes et al. (2017) tried to create a meaningful and easily understood metric for combining frequency, duration, and intensity necessary to achieve optimal health results from heart rate derived data (Nes et al., 2017). These authors developed a metric named 'Personalized Activity Intelligence' (PAI), an algorithm based on continuous heart rate monitoring and designed to replace self-reported intensity, duration, and frequency with measured heart rate. Data derived from cumulative 7-day heart rate monitoring was obtained in 39,298 participants aged 20-74 years, with PAI calculated for each participant. PAI gives greater scoring for vigorous physical activity compared to moderate or light physical activity, and an overall score was obtained. PAI categories were <50, 50 – 99, ≥ 100 while an inactive group (PAI = 0) were used as the reference category. The study reported that obtaining ≥ 100 PAI was associated with a 17% (95% CI 7-27%) and 23% (95% CI 4-38%) lower risk of cardiovascular disease and mortality in men and women respectively, compared with the inactive groups in all age categories and sexes. More interestingly, was a separate analysis assessing hazard ratio for the combination of PAI and government physical activity recommendations. Those participants who did not meet government physical activity guidelines (150 minutes of moderate intensity or 75 minutes of vigorous intensity activity per week) but scored ≥ 100 PAI were not at a higher risk of all-cause mortality hazard ratio 1.06, 95% CI 0.94 – 1.19) or CV disease (hazard ratio 1.07, 95% CI 0.87 – 1.31). Although it is worth noting, there is a high level of uncertainty within these findings, plausible risk could range from a small reduction (~10%) to a large increase (~30%). In comparison, participants who met PA guidelines, but had a PAI <100 had a greater risk of all-cause mortality (1.13, 95% CI 1.02 – 1.24) and CVD (1.27, 95% CI 1.09 – 1.48), suggesting that exercise intensity, and the subsequent CRF benefits may play a greater role in reducing CVD and all-cause mortality risk compared to exercise duration and accumulation. Authors are not the first to disseminate a training intervention that modifies duration based on intensity. TRIMP or Training IMPulse is a method of quantifying aerobic training load and is a product of training volume, measured in minutes and training intensity measured as average heart rate (Calvert et al., 1976). Never-the-less these findings are important for physical activity guidance, and a greater emphasis may need to be placed on physical activity intensity to ensure, relative moderate intensity is adequately reached.

A recent review also highlighted the need for change in physical activity guidelines due to their systemic failure to reduce CV, renal, pulmonary and metabolic diseases (Lehtonen et al., 2022). Lehtonen et al. (2022) developed a hierarchical framework to improve exercise prescription. Authors reported large interindividual variability of CRF as one of the main factors contributing to the reduced capability of physical activity guidelines, suggesting that physiological responses to physical activity are partly explained by two contributing factors - biological and methodological. Biological factors include genes, sex, age, as well as cardiorespiratory markers such as VO_{2max} and heart rate variability (Meyler, Bottoms and Muniz-Pumares, 2021). Additionally, methodological factors such as individual differences in training status and response are considerations that need to be accounted for when considering physical activity dose and should be considered on an individual basis. For example, Montero and Lundby (2017) studied CRF non-responders (i.e., those who report to be meeting physical activity guidelines but do not show any improvement in CRF) to differing exercise volumes. Authors reported a decreasing number of non-responders with increasing weekly training volume, from 60, 120 and 180 minutes per week (n=16, 11 non-responders, n=15, 6 non-responders and n=14, 4 non-responders respectively). No non-responders occurred at 240 minutes of activity, as well as 300 minutes of weekly endurance training split into 60-minute sessions on a cycle ergometer. Additionally, those initial non-responders were subsequently given two additional 60-minute sessions per week, which eliminated all non-responders. More interestingly is the proportion of non-responders (29%) exercising above government recommended exercise guidelines for moderate intensity (performing a mean of 180 minutes per week), which may indicate that for CRF improvements to occur, current physical activity guidelines of at least 150 minutes might not be sufficient in healthy adults and those with a CRF above mean population level. Of note is the small sample sizes for each group (N=16,15, and 14) and the selection of healthy adults. Those adults who may be classed as unhealthy, non-exercising, or have co-morbidities, may require significantly less volume, potentially highlighted by the number of responders at 60 (5) and 120 (9) minutes per week of moderate intensity who could have potentially had lower CRF than the group mean. Non-the-less, the findings identify the need for individualisation of exercise prescription, as sufficient volume of training to obtain changes in CRF remains highly individualised.

Lehtonen et al. (2022) also investigated the role of training intensity as an important variable for optimal CRF adaptations. A key consideration for general physical activity guidelines is the role of intensity in determining the minimum amount of physical activity vs CRF improvements. In other words, what is the minimum intensity required to improve CRF. A review conducted by Swain and Franklin (2002) identified that an individual's CRF impacted the intensity required to improve VO_{2max}. These authors reported that a training intensity of 45% VO_2R was consistently ineffective in improving CRF for participants with a VO_{2max} > 40 $mL·kg^{-1}·min^{-1}$. However, for participants with a VO_{2max} < 40 $mL·kg^{-1}·min^{-1}$ no intensity was found to be ineffective (the lowest intensity examined was 30% VO_2R) for improving CRF. However, small sample sizes (4-9) may have impacted results of the higher CRF (>40 $mL·kg^{-1}·min^{-1}$) group (Davies and Knibbs, 1971; Burke and Franks, 1975). For context, a recent normative reference values for CRF, in apparently healthy British women and men was conducted retrospectively (Ingle et al., 2020). All participants had completed a VO_{2max} test as part of a preventative health assessment held by their corporate wellness scheme. 9,204 men and 2,697 women, participated in the investigation, median $mL·kg^{-1}·min^{-1}$ (25^{th}, 75^{th} centile) for men 36.9 (30.5, 44.7) $mL·kg^{-1}·min^{-1}$ and women 36.5 (30.1, 44.8) $mL·kg^{-1}·min^{-1}$ mean the implications of training intensity dependent on CRF fitness may play an integral role in the population. There is a strong indication from the literature that baseline CRF modifies the intensity required to improve CRF.

2.6 Understanding government guidelines

One of the issues not highlighted in the review by Lehtonen et al. (2022) is whether physical activity guidelines are clear and therefore understood by members of the public. This issue has been examined in several studies (Ronda, Van Assema and Brug, 2001; Vaara et al., 2019; Piercy et al., 2020). Vaara *et al.* (2019) investigated young adult men's understanding of government guidelines to physical activity in 776 participants in the UK. While 40% of participants were aware, in some form or another that physical activity recommendations existed, only 7% were able to correctly identify the 150 minutes of moderate intensity physical activity a week, recommended in the government guidelines to physical activity. Additionally, Ronda, Van Assema and Brug. (2001) investigated awareness of physical activity levels in 2608 adults in the Dutch population, using structured questionnaires. Results indicated that 60% of respondents were overestimating their physical activity completion, indicating whilst understanding government guidelines for physical activity is important, understanding physical activity completion may also play a significant role. More recent investigations have also seen a similar trend, Piercy *et al.* (2020) similarly recruited adults aged 25 – 74 years old within the United States, 2,050 participants completed the online survey. Results indicated only 22% of participants were aware of government guidelines to physical activity. Similarly in a UK population of 2860 adults, an online survey was disseminated in 2007 and 2013, again similar findings were reported with 11% and 18% of the sample accurately able to recall the government guidelines to physical activity (Knox et al., 2013). Whilst results may have improved over the 6-year period less than one in five of those recruited were able to accurately identify physical activity guidelines. Although all these studies have adequate sample sizes, the findings may be impacted by the use of questionnaires as data collection methods, whilst questionnaires are good at obtaining information from large sections of the population, they often lack reliable and valid findings and do not offer the opportunity to probe for additional information (Burcu, 2000). None the less these findings highlight, across the spectrum of the last 20 years, understanding of government guidelines to physical activity are not well acknowledged or understood. Additionally, WHO have reported insufficient activity has increased by 5% from 31.6% to 36.8% in high income countries from 2001 – 2016 (WHO, 2020). The importance of increasing physical activity in the general population cannot be understated, and evidence spanning 20 years suggests many populations understanding of physical activity in several countries, and demographics across the population are not aware or do not understand government guidelines to physical activity, improving physical activity participation is therefore a worldwide problem.

2.7 Relative and absolute intensity physical activity

There is currently no gold standard measure of physical activity intensity. The ACSM has a range of measures that can be used to indicate intensity cut point thresholds including METs, %HRmax, %$VO_{2max,}$ %HRR, %VO_2R (Liguori, 2022). The implications for this wide spread of intensity variables are that they are not all equal. Cardiorespiratory health has a large impact on the walking speed required to meet relative moderate intensity, and some of these measures (METs) do not take into consideration cardiorespiratory health. METs are a well-established method of monitoring physical activity (Jetté, Sidney and Blümchen, 1990) often used in conjunction with an accelerometer (Harrington et al., 2012; Tudor-Locke et al., 2018; Aguiar et al., 2019). However, METs offer very little individualisation as they do not take into consideration cardiorespiratory health (Iannetta et al., 2021). Additionally, there are discrepancies in how METs are measured, as highlighted by the recent meta-regression (Chapter 4), METS can be completely absolute whereby physical activity is estimated using standardised values, that are the same for everyone, and are based on a resting 1 MET value of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$. A hybrid version of METs also exists whereby breath-by-breath analysis is divided by a standardised value of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ to provide a MET intensity. And finally, a measured MET whereby breath-by-breath analysis is divided by an established individualised MET value as measured by resting VO_2 (chapter 4). Whilst other measures use some form of cardiorespiratory health, there may be a continuum of physical activity measures, from completely absolute to completely relative. At the absolute end of the spectrum there is estimated METs. Along from this there are hybrid measures that take some cardiorespiratory measures into consideration, such as %HRmax, and $\%VO_{2max}$, but only use a maximal value to predict exercise intensity thresholds from. Perhaps a better, more relative measure would be %HRR and $\%VO_2R$ that use both a lower and upper bound of an individual's cardiorespiratory capabilities, and at current, may offer the most individualised and accurate practical measure, that can be integrated easily into daily living within the public, through wearable technology. However, whilst bounds are based on research (Liguori, 2022) these values are not individualised, for example, 40 – 59% HRR equates to moderate intensity, but a fixed bound for all individuals, this lower bound of moderate intensity may require adjusting in populace with poor cardiorespiratory fitness. Finally lactate threshold and ventilatory thresholds possibly offer the most individualised intensity thresholds and thus the most relative form of physical activity intensity monitoring, as they are measuring a real physiological threshold, as opposed to arbitrary percentage threshold markers (Iannetta et al., 2020). It has been reported that when exercise intensity is anchored to individual ventilatory thresholds, the metabolic stimulus is better normalised across people with varying cardiorespiratory fitness (Weatherwax et al., 2019). However, whilst these measures are likely to be the most accurate, the ability to measure such values during daily living is near impossible as it requires expensive laboratory equipment and a trained professional.

2.8 Training intensity thresholds

Relative training intensity thresholds are required to accurately prescribe and monitor physical activity (chapter 4). In elite athletes' a polarised training approach has been shown to effectively improve CRF (Stöggl and Sperlich, 2015). The mechanistic reason for this is thought to be the combination of low and high intensity training might cause similar adaptations in skeletal muscle via different molecular pathways, while low intensity training might also promote autonomic balance and recovery (Laursen, 2010). Polarised training is an approach targeting most training time at an intensity below the first ventilatory threshold ($VT_{1)}$ and above the second ventilatory threshold (VT_2) with limited training between ventilatory thresholds (Lehtonen et al., 2022). Although there is conflicting evidence to suggest polarised training may not be optimal for endurance athletes (Burnley, Bearden and Jones, 2022), and that an appropriately balanced training intensity distribution across training zones is more effective for endurance performance.

Never-the-less there is emerging evidence suggesting this training approach may work in recreational athletes and in young overweight and obese populations (Hydren and Cohen, 2015; Zapata-Lamana et al., 2018). Further investigation is warranted, as previously reported findings suggested that HIIT may offer additional CRF benefit compared to lower intensities. However, as previously stated, adherence to HIIT is low (Ekkekakis and Biddle, 2023; Ekkekakis et al., 2023) and this is likely to impact adherence to polarised training whereby some of the training is performed above the second ventilatory threshold. A combination of low/moderate intensity and HIIT may offer more enjoyment and be more practical in certain population groups who are able to sustain the intensity required to meet vigorous/high intensity exercise.

Although HIIT, vigorous intensity physical activity, and moderate intensity physical activity have seen a wealth of research on their potential benefits, light intensity physical activity has not seen the same volume of investigation. There is a growing bank of evidence that light intensity might be adequate in developing cardiometabolic health benefits. A recent review (Chastin et al., 2019) of 72 studies (27 experimental and 45 observational studies) reported that short but frequent bouts of light intensity physical activity dispersed throughout the day reduced postprandial glucose and insulin level compared to continuous sitting (ES = -17.5% [95%CI: -26.2 to -8.7), (ES = -25.1% [95%CI: -31.8 to -18.3) for glucose and insulin respectively. These studies were completed on healthy participants or drawn from metabolically impaired populations. However, whilst postprandial glucose and insulin levels were reduced acutely, the long-term benefits of low intensity physical activity were not investigated.

Although the evidence may suggest some benefit of light intensity physical activity, current government guidelines to physical activity focus on moderate and vigorous intensity. As previously discussed, exercise that has the capacity to create behavioural change, and integrate physical activity into daily life, is likely to be the most successful. As reported by Ekkekakis and Biddle (2023), vigorous intensity physical activity and HIIT reduce long-term adherence compared to moderate-intensity physical activity, and subsequently may not offer the best method for inducing behavioural change (physical activity fidelity and adherence) at a population level. It is likely that moderate intensity is the best option when considering all the potential influences and subsequent barriers to physical activity that exist in modifying behaviour. Walking is the most common form of physical activity performed at a population level (CDC, 2013; Sport England, 2020), and moderate intensity can be attained from walking (Serrano et al., 2017; Slaght, Sénéchal and Bouchard, 2017; Abt et al., 2019). In recent years moderate intensity walking has focussed on an absolute approach to walking cadence prescription, with a number of authors advocating 100 steps$\cdot$min^{-1} as the threshold for moderate intensity (Rowe et al., 2011; Tudor-Locke et al., 2018; Aguiar et al., 2019). However, there are several practical limitations with this one size fits all approach to exercise prescription. As previously discussed, the largest influence on intensity cut-point thresholds is CRF, therefore, someone with high CRF may require a faster cadence to reach moderate-intensity physical activity (Abt et al., 2019). Other authors (Beets et al., 2010; Ayabe et al., 2011; Rowe et al., 2011; Peacock et al., 2014) have highlighted that it's not just CRF that influences the cadence required to reach moderate-intensity physical activity, but a number of biological and physiological variables also play an important role in determining the walking cadence required to reach moderate intensity.

2.9 Factors affecting walking cadence

2.9.1 Stature

There are number of factors that influence the cadence required to achieve moderate-intensity physical activity. Walking speed is the product of step length and step frequency (Beets et al., 2010), therefore leg length influences the step length. Stature, or more specifically leg length, has an influence on the walking cadence required to reach moderate intensity physical activity. Rowe and colleagues (2011) investigated the impact of stature on walking cadence in 75 university employees. At three randomly assigned, evenly distributed speeds, set to replicate slow, medium, and fast walking, participants performed treadmill trials while oxygen consumption was measured. These three speeds were then replicated over ground with cadence cueing used to direct participant walking speeds. Cadence 'cueing' involves matching walking cadence with the rhythmic flow of a metronome or external stimulus such as music. Results indicated a relationship between stature and walking cadence, such that to reach criterion, absolute moderate intensity (equivalent to 3 METs) cadence varied by more than 20 steps·min^{-1} depending on participants' stature. Cadence at 3 METs varied from 90 to 113 steps·min^{-1} for participants ranging from 152 to 198 cm tall, respectively. Similar results were reported at higher intensity: at 5 METs participants' walking cadence ranged from 128 to 151 steps·min^{-1}, indicating that shorter participants required a faster cadence to reach the same required absolute intensities. Peacock et al. (2014) performed a similar investigation in 29 adults (mean (SD) age 32 (12) years). Results also indicated stature impacted cadence requirements (82 and 113 steps·min^{-1}) to meet absolute moderate-intensity physical activity (3 METs). Additionally, participants performed overground walking trials at pre-determined slow, medium, and fast speeds (based on the treadmill trials). Participants on average walked at a mean (SD) of 111 (9.3) steps·min^{-1} in the slow condition, somewhat higher than the 100 steps·min^{-1} the author advocates as a general public health message and in line with other author recommendations (Tudor-Locke et al., 2005; Marshall et al., 2009).

Similarly, when leg length is measured, the same findings are reported. Beets et al. (2010) reported a variance of 88-111 steps·min^{-1} dependent on leg length at 3 METs. These authors concluded that as leg length increased, the required steps·min^{-1} decreased by 1.15 steps·min^{-1}. O'Brien et al. (2018) proposed that for every 10 cm increase in leg length, the cadence required to elicit moderate-to-vigorous physical activity (MVPA) decreased by 5 steps·min^{-1}. Therefore, the shorter the leg length (and therefore shorter stature) the higher the cadence required to reach absolute moderate-intensity physical activity.

2.9.2 Age

There is general consensus that older adults predominantly walk more slowly than their younger counterparts (Ayabe et al., 2011; Tudor-Locke et al., 2011; Peacock et al., 2014). Tudor-Locke et al. (2011) investigated peak 30-minute and peak 1-minute cadences through the National Health and Nutrition Examination Survey (NAHNES). The health surveillance sample 2005-2006, reported that age-related decline in walking speed was observed, with a far greater degradation after 60 years of age. Mean peak 30-minute cadence for 20-29, 30–59 60-69 and 70+ year olds was: 77, 75, 65, and 53 steps·min^{-1} respectively. One-minute peak cadence was similar, with a decrease from 107 to 82 steps·min^{-1} for 20-29 to 70+ year olds, respectively. These large declines in peak cadences post 60 years might be explained by a reduction in muscular strength (Delmonico et al., 2009), type 2 muscle fibre type, and muscle fibre recruitment capabilities (Nilwik et al., 2013). Lower stride rates may be caused by age-related biomechanical constraints, a decrease in muscle mass, strength, and muscle contraction speed (Song and Geyer, 2018) which expresses itself biomechanically as a reduced stride length (Nagasaki et al., 1996). Previous literature has suggested the metabolic cost of walking in older adults is higher than young adults (Jones, Waters and Legge, 2009). However, a recent meta-analysis (Das Gupta, Bobbert and Kistemaker, 2019) highlighted a number of flaws within this area of research, mainly the way metabolic cost of walking is expressed, the units in which they are recorded, and the walking speed at which it was measured. Authors calculated and reported gross and net metabolic cost of walking, with healthy young adults (18 – 41 years) having a mean gross metabolic cost of walking of 3.4 (0.4) $J \cdot kg^{-1} \cdot m^{-1}$ compared to 3.8 (0.4) $J \cdot kg^{-1} \cdot m^{-1}$ in older adults (>59 years), approximately 12% more in older adults. However, authors concluded that it is unclear whether the increased metabolic cost is due to age or an interaction between age and methodology (i.e., the older adult's familiarity with treadmill walking or laboratory-based protocols).

Although cadence reduces with age, its impact on whether older adults can achieve moderate intensity physical activity, is questionable, because CRF declines (Jackson et al., 2009). That is, although walking cadence is slower in older people, their lower CRF may still allow a slower cadence to elicit moderate intensity physical activity as fitness status plays a significant role in intensity prescription (Abt et al., 2019). Using the current absolute approach to physical activity, older adults are, like all healthy populations, being encouraged to walk at an intensity of 3 METs, or approximately 100 $steps \cdot min^{-1}$. According to Tudor-Locke et al. (2011) older populations are not meeting these walking intensity guidelines during free living conditions. However, these guidelines are based on an absolute measure of intensity which does not account for age-related reductions in CRF, which accelerates from approximately 45 years of age (Jackson et al., 2009). Additionally, Martin et al. (1992) reported that the metabolic cost of walking in elderly populations over the age of 70 years was 15-30% higher than for people in their 20s. Therefore, while older adults may not be walking at the prescribed 100 steps·min^{-1}, when expressed relative to their CRF they may still be able to achieve moderate intensity.

There is also evidence that older adults can walk faster but choose not to do so under free living conditions. Peacock et al. (2014) reported that when older adults (mean (SD) 46 (16) years) were verbally instructed to walk at self-paced slow, medium, and fast speeds in laboratory-based trials, participants exceeded MVPA (defined as 3 METs) in all walking conditions. The minute epoch used to 'chunk' data into smaller units could explain their inability to meet the required cadence during free living. As cadence in free living conditions is often measured via an accelerometer and measured in steps per minute, steps are quantified over this same period (i.e., the number of steps completed in one minute). This is only strictly true if walking is continuous within that epoch (Dall et al., 2013). When minute epochs were analysed individually, Dall and colleagues reported that 32% of active minutes contained less than 10 seconds of walking and 69% of all active minutes contained 30 seconds or less of walking. Put simply, a participant could be walking at 150 steps·min^{-1} for 30 seconds thus meeting MVPA guidelines and then stop walking, this would be recorded as a cadence of 75 steps·min^{-1} within a minute epoch. This may explain why some older adults do not meet the required cadence to reach MPA as they are simply not walking for a long enough duration. Although there is research examining the duration of intensity required to improve CRF fitness (Garber et al., 2011; Nakahara, Ueda and Miyamoto, 2015), more research is required to understand the smallest duration of physical activity required to improve CRF.

2.9.3 Body mass

Body mass and BMI may also play a pivotal role in one's ability to meet the recommended MVPA guidelines. A number of authors have reported a reduction in walking cadence in higher BMI and body mass categories (Ayabe et al., 2011; Tudor-Locke et al., 2011; Pillay et al., 2014). Tudor-Locke et al. (2018) reported peak 1-minute and 30-minute cadences for BMI categories. The results indicated a reduction in walking cadence between normal body mass and participants with obesity. It was reported that each category increase in BMI (i.e., normal – overweight – obese), saw a reduction in 30-minute (76, 73.4, 63.8 steps·min^{-1} respectively) cadence. Interestingly, in underweight participants a reduction in peak cadence was also observed when compared with those of normal body mass. Peak 30-minute walking cadences were 66.0, 76.0 and 57.3 steps·min^{-1} for underweight, normal, and obese categories, respectively.

Ayabe et al. (2011) observed daily physical activity patterns in normal and overweight participants. Activity time was categorised as: light (<3 METs), moderate (3-6 METs), and vigorous (<6 METs) intensity. Normal weight participants spent significantly more time in all 3 physical activity categories compared to their overweight counterparts (normal weight, mean [SD] Light 82.5 [23.9], moderate 45.4 [22.5], vigorous 7[6.0] mins·day^{-1}, compared to overweight Light 53.4 [20.8], moderate 21.4 [14], vigorous 0.9 [0.9] mins·day$^{-1.}$). These trends also translated into cadence-based parameters with overweight participants recording significantly fewer minutes in cadence brackets associated with light (<100 steps·min^{-1}) moderate (100-129 steps·min^{-1}) and vigorous (<130 steps·min^{-1}) intensity and significantly fewer overall daily steps (normal weight, mean [SD] Light 300 [81], moderate 23 [15], vigorous 7 [7] mins·day^{-1}, overall steps 11,076 [3165] steps·min^{-1}, compared to overweight, Light 267 [85], moderate 14 [9], vigorous 1 [1] mins·day^{-1} overall steps 7270 [2990] steps·min^{-1}). However, as this data was collected via absolute methods, and does not take into consideration cardiorespiratory health, it is likely that those participants who were overweight and obese had less CRF compared to their normal weight counterparts. It is therefore likely, that the cadence required to elicit moderate and vigorous intensity in the overweight/obese group was lower than the 100 – 129 steps·min^{-1} and > 130 steps·min^{-1} reported in this study, and therefore if physical activity was measured using relative measures it is likely the overweight and obese group would have reported more physical activity (Kujala et al., 2017). Pillay et al. (2014) published similar findings, with BMI, waist circumference, and body fat percentage all having a negative impact on total daily step count, aerobic intensity of physical activity performed, and time spent performing aerobic activity. The burden of carrying additional mass could explain the reduction in absolute physical activity completed. Browning and Kram (2005) reported that the energetic cost of preferred walking speed in obese women was 11% higher than normal weight participants, even though this preferred walking speed was slower than their normal weight counterparts, it still required a greater relative aerobic effort (51% VO_{2max} vs. 36% VO_{2max}) to carry the additional mass. The burden of carrying extra mass may also reduce participants' walking efficiency and economy. Obese people tend to have shorter stride length, larger step width, and smaller cadence (Spyropoulos et al., 1991; Ayabe et al., 2011). Considering the extra physiological burden body mass has on the cardiorespiratory system, the required cadence to reach moderate intensity physical activity may be substantially lower than the 100 steps·min^{-1} reported. Serrano et al. (2017) investigated relative exercise intensity prescription and the cadence required to reach 40% VO_2R. Their findings suggested that for every additional 10 kg in body mass, the walking cadence required to reach 40% VO_2R reduced by 2.5 steps·min^{-1}.

2.9.4 Sex

There is evidence to suggest differences in walking cadence also exist between sexes. It is thought that for females to walk at the same speed as males, their cadence has to be higher at both moderate 94 compared to 99 steps·min^{-1} and vigorous, 99 and 135 steps·min^{-1} respectively (Abel et al., 2011). The difference in cadence associated with sex could be due to differences in stature. Abel et al. (2011) reported that females were substantially shorter than males (mean (SD) 1.60 (0.09) m vs 1.82 (0.08) m). However, several authors have reported differences in gait patterns between males and females that may also be attributed to differences in cadence. At self-selected speeds without assistance or instruction, females walk with a higher cadence and shorter stride length. Females also have reduced hip range of motion, and greater range of motion at the ankle in the sagittal plane (Ko et al., 2012). Additionally, Bruening et al. (2015) also observed differences in the hip and ankle motion between sexes. Specifically, females had greater pelvic obliquity, exhibited a more stable torso in the frontal plane, and increased torso rotation in the sagittal plane. Authors also reported differences in the upper body, with females having greater arm swing. These biomechanical differences have the potential to affect walking economy and thus alter the required cadence to elicit MVPA.

2.10 Strategies to increase cadence

Given there are several variables that contribute to walking cadence, and research has highlighted adults under free living conditions may not meet the walking speed required to reach MPA, several authors have developed strategies to guide participants to a desired walking speed. One of the most used methods is cadence cueing. Using a metronome, participants are guided to the desired walking speed, usually by instructing them to replicate or match their walking cadence to the beat or pulse of the metronome. This method has been used to prescribe walking intensity with relative success in healthy populations (Rowe et al., 2011; 2013; Ducharme et al., 2018). Music tempo has also been used to direct walking cadence with positive findings (Wittwer, Webster and Hill, 2013; Peacock et al., 2014). Using a similar method as metronome cues, participants are instructed to match their walking cadence to the music tempo. More simplistic methods have also been successfully incorporated. Verbal cues to encourage participants to walk at differing speeds have been investigated as a means of prescribing walking intensity (Canning et al., 2014; Minahan et al., 2019). Simple directive instruction to walk at a self-prescribed speed can have the desired effect in increasing walking pace and subsequent intensity (Fitzsimons et al., 2005). Alternatives to cadence cueing have also been investigated, such as pedometers, accelerometers, and wearable devices that provide visual feedback and positive reinforcement when reaching the required walking cadence (Bouchard et al., 2013; Slaght, Sénéchal and Bouchard, 2017). Cadence cueing can guide users to a higher cadence, with the potential to increase attainment of moderate and potentially vigorous physical activity.

2.10.1 Auditory cueing

Using a metronome to guide walking cadence is in theory, a simple, inexpensive method that could be used to guide participants to a desired walking speed and subsequent physical activity intensity. Auditory cueing consists of instructing participants to synchronise each step taken to the beat of a metronome over time or distance. The metronome can be set to a tempo that replicates the required cadence and altered depending on population, fitness status, physiological and biomechanical differences, and gender to elicit the required intensity. Ducharme et al. (2018) examined auditory cueing by having 16 healthy adults complete walking trials while attempting to synchronise their cadence with metronome cues set to a tempo between 80 – 140 beats·min^{-1}. Mean absolute percentage error was calculated to compare walking cadence with metronome tempo across 8 trials of differing cadences, across a 13 m walkway, and repeated 12 times. Results indicated that participants successfully matched their walking cadence with the metronome cue to within <1.1% mean absolute percentage error. Whilst the study indicates synchronisation may be plausible, completing walking trials over a 13m walkway 12 times does not replicate walking outside, where road infrastructure and other pedestrians may cause disruption to walking cadence, additionally participants performed trials for a relatively short duration, and it is likely that this is a shorter duration does not replicate outdoor walking, and thus the ability to continually synchronise to a metronome for a sustained period may be more difficult. Rowe et al. (2011) also tested the applicability of metronome cues, but with inactive adults. Participants performed treadmill trials at 4.3 km·h^{-1} while cadence was recorded. Participants then performed over ground trials at the same cadence, directed via a metronome cue. Mean (SD) cadence for the treadmill trial was 114 (8) steps·min^{-1} which was successfully replicated in the over ground trials within 3 steps·min^{-1} in 23 of 25 participants.

However, how cadence was measured in the overground trials has not been reported, and thus the validity of these measures cannot be scrutinised. Moreover, participants' cadence during treadmill trials was measured via a hand-counted tally counter. Participants' ability to synchronise their walking cadence accurately with a metronome or audio cue may prove more difficult as walking cadence increases. Peacock et al. (2014) reported participants were able to synchronise their walking cadence above or below their natural walking cadence when synchronised to an audio beat. The authors reported that in the context of walking, differences between music tempo and cadence were insignificant, and participants possessed a sufficient ability to increase or decrease their cadence to match the tempo they were hearing. These authors concluded it may be unrealistic to expect participants to be able to synchronise their walking cadence to an audio cue accurately. Nonetheless, music and metronome cues could guide walking cadence, and thus could improve walking speeds in an adult population.

Music can also be used to guide walking cadence in a similar fashion using the synchronous beat to provide an ergogenic aid. Music can also enhance walking, running and general exercise intensity beyond that of a cue, increasing stimulus and other physiological and psychological benefits that may elevate its motivational ability over the metronome (Karageorghis and Priest, 2012; Terry et al., 2012; English, Mavros and Jay, 2019). In exercise performance, music can also alleviate mental discomfort and improve one's ability to perform physical activity for longer (Macone et al., 2006). The ergogenic benefits of using music as a motivational tool during exercise has the ability to improve performance by enhancing positive effect, lower rating of perceived exertion, improve energy efficiency, and potentially increase work output (Terry et al., 2012). There is also evidence to suggest that when music is carefully chosen, it can promote ergogenic and psychological benefits during high intensity exercise, and have an increased benefit when exercise is performed at a self-selected intensity (Karageorghis and Priest, 2012).

However, whilst music may have additional benefits over a metronome, the ability to cue cadence is impacted by several variables. Music depending on genre has the ability to impact mood, behaviour, tension and mental clarity (McCraty et al., 1998; Ahmad and Rana, 2015). Whilst metronome synchronisation is effective at cueing cadence over short distances (Dickstein and Plax, 2012; Wittwer, Webster and Hill, 2013) synchronising walking cadence to music may be more difficult as elements within music such as dynamics, duration, rhythm, structure, melody, instrumentation and harmony may impact one's ability to synchronise with the tempo of the music accurately (Clayton, Jakubowski and Eerola, 2019). Franěk, van Noorden and Režný, (2014) investigated the impact of music tempo and motivational music, defined as music that has a fast tempo and strong rhythm, compared with music that was slower, with no strong implication for movement. Seventy-nine young adults aged 19- 25 years old, performed the two walking conditions on a 1.8 km circuit through urban city spaces in Hradec Králové, Czech Republic. Routes were pre-planned with markings on the pavement to guide participants, who had been given a map of the route a week in advance of the trials. Participants initially performed a non-music trial from which walking cadence was aligned with 1 of 3 musical playlists including 9 songs of different tempi that closely replicated the participants walking speed. This playlist was then used for the motivational music condition. Results indicated of the 79 participants; 38 participants did not synchronise with any of the tracks. Participants rarely spontaneously synchronised with the beat of the music, and some participants synchronised only part of the time. Of the tracks synchronisation was most common with track 5, whereas very few participants managed to synchronise with tracks 3, 4 and 6. Interestingly, the track with the most synchronisation had a tempo of 187 bpm. Whereas track 3, 4 and 6 had a tempo of 135, 158, and 192 respectively. The study experimental instructions may have impacted synchronisation in the motivational music condition, as in both trials participants were told to walk at their normal walking speed and not explicitly told to synchronise their walking cadence with the music. Additional analysis on the impact music tempo had on walking speed was completed. The results indicated that the type of music (motivational or non-motivational) had a strong effect on walking speed in particular sections. The mean walking speed for motivational music was mean (SD) 1.67 $m{\cdot}s^{-}1$ (0.17) and for non-motivational music was 1.47 $m{\cdot}s^{-1}$ (0.14).

It is well reported that music causes humans to move (Shiobara, 1994; Nusseck and Wanderley, 2009; McGarry, Sternin and Grahn, 2019). There are several behavioural and neuroscientific characteristics that impact the way in which the human body moves to music, neuroticism is associated with jerky and accelerative movement, while personality traits such as openness to experience and agreeableness tend to be related to smoother movement. Extroverts and conscientiousness have been related to higher speed movement (Nusseck and Wanderley, 2009). Beat perception abilities, body shape, age, cultural background and musical and dance training all impact the way people move to music (McGarry, Sternin and Grahn, 2019). So, whilst music may offer additional benefits compared to a metronome (Karageorghis and Priest, 2012; Terry et al., 2012), the complexity of music composition in comparison to a simple metronome and the impact music has on different people and subsequent impact this could have on walking speed, gait and cadence may mean that using a metronome to cue cadence is a more simple and easier method to synchronise cadence too.

2.10.2 Verbal cues

Some authors have tested participants' ability to self-select a walking speed that they believe constitutes moderate intensity physical activity (Canning et al., 2014; Minahan et al., 2019). More interesting, is whether giving participants a verbal instruction such as 'walk briskly' increases their cadence above habitual walking speeds. Canning et al. (2014) asked participants to complete four self-selected intensity walking/running trials, with the following instructions: Light – you are starting to feel warm, and you have a slight increase in breathing rate (50 – 63 %HR_{max}), Moderate – you are warmer, and you have a greater increase in breathing rate (64 – 76 %HR_{max}), and Vigorous – you are quite warm and out of breath (77 – 93 %HR_{max}). The instructions given were adopted from intensity descriptors that are used in physical activity guidelines worldwide (Canning et al., 2014). Results indicated that participants were able to self-select light intensity physical activity (51.5 ± 8 %HR_{max}) but underestimated moderate (58.7 ± 10.7 %HR_{max}) and vigorous (69.9 ± 11.9 %HR_{max}) intensities. One final trial was completed using the following cue 'walk at the minimum pace that you believe will provide health benefits.' Participants completed this trial at an average intensity of 57.46 ± 10.5 %HR_{max}, which is less than the predetermined moderate intensity guideline range (64 – 76 %HR_{max}). Based on the pre-determined intensity thresholds, 52% of participants performed at a light intensity (56.86 ± 3.8% HR_{max}), 19% at a moderate intensity (67.6 ± 5.5% HR_{max}) and only 5% at a vigorous intensity (85.36 ± 9.6 %HR_{max}). The spread of data across intensity thresholds indicates participants uncertainty in how hard to exercise when given verbal cues. Additionally, most participants underestimated the intensity required to meet relative intensity MPA, when instructed to exercise at the minimum walking speed they perceived would meet MPA. These findings have implications for exercise guidelines.

Minahan et al. (2019) conducted a similar study but in older women. Participants were instructed to 'walk at a speed deemed appropriate for 30 minutes of exercise.' Trials were performed at self-paced, over ground, and on a treadmill. Percentage HR_{peak} was 61 - 75% for overground trials and 63 - 74% for treadmill trials, which corresponded to 94% and 87% ventilatory threshold, respectively. From these findings, the authors reported that women can self-select a walking speed that induces metabolic load approximating the ventilatory threshold, both overground and on a treadmill. However, it is unclear whether participants would self-select this speed habitually when walking under free-living conditions. The instruction in both Canning et al. (2014) and Minahan et al. (2019) investigations regarding 'health benefits,' and 'exercise' may have increased participants cadence above their subconscious habitual walking speed. Certainly, when compared to cadence reported under free-living conditions (Tudor-Locke et al., 2011) the mean cadence in both trials is substantially higher, even though there is evidence to suggest participants struggled to identify a suitable walking cadence to elicit health benefits (Minahan et al., 2019). The perception reported in those studies was that a faster walking cadence than normal was required to gain health benefits. One reason for this could be due to the subjective nature of the instructions. Equally, a participant's ability to correctly identify the required walking cadence could be affected by a number of factors such as emotional and physical state and self-awareness (Minahan et al., 2019). An alternative could be to give clearer instructions on the walking cadence required to reach MPA. Bouchard et al. (2013) randomly allocated participants into 3 groups: self-selected walking goal with no recommendations for daily or weekly walking; a 10,000 steps per day goal (frequency), or 3000 steps in 30 minutes (cadence). While all groups increased their MVPA over the 12-week intervention, the cadence group significantly increased their MVPA when compared to baseline and when compared to both the self-selected and frequency groups. Although the instruction was not a specific verbal cue before participants performed each walk, it suggests short-term objective goals are easier to use, compared to subjective instructions that are based on feeling and thought.

2.11 Subjective measures of physical activity

It is not always feasible to objectively measure physical activity. Objective methods can often be inhibited by cost, and a willingness to use technology, especially in older populations (Ma, Chan and Teh, 2021). A simplistic method to overcome this is self-reporting of physical activity. There are, however, a number of issues with this method that often stem from the large overestimation of self-reported MPA (Colley et al., 2011). These large overestimations in physical activity completion were highlighted in the NHANES survey when subjective, self-reported physical activity was compared to objective, accelerometer data. 51% of adults self-reported completing a minimum of 150 minutes of MVPA a week, whilst accelerometer data showed only 5% were accumulating this level (Troiano et al., 2008). Even in intervention-based research whereby participants have received training in the identification of MVPA and given tools including heart rate monitors and pedometers to measure intensity, their ability to subjectively measure physical activity does not improve post-intervention (Bouchard et al., 2013). The high level of error could be due to, in part, people’s ability to correctly identify MVPA and their limited understanding of physical activity intensity thresholds. For records to be accurate, participants not only have to self-assess their intensity in forms that are often unanchored (e.g., RPE) but also must accurately report total completed time. When you consider the behaviour of pedestrians and crowds walking in social situations, between physical and environmental constraints, where a trade-off between walking speed and social interaction occurs, this will undoubtedly have a subsequent effect on MVPA being performed. Moreover, given the difficulty for participants to concentrate to maintain a given intensity, take note of this varying intensity, and the duration it has been performed, (Moussaïd et al., 2010), it is easy to see why such high levels of variance in self-reporting occur.

Governments around the world have tried to address the lack of physical activity being performed at a population level by introducing physical activity guidelines such as the UK, NHS guidelines to physical activity (nhs.uk, 2022). Currently, NHS guidelines encourage people to perform 150 - minutes of moderate or 75-minutes of vigorous intensity, or a combination of the two, a week, as well as two resistance sessions. The UK physical activity guidelines were initially devised in the 1990's. The Health Education Authority was responsible for advising the government on a health-related strategy (Milton and Bauman, 2015). In 1996 a strategy statement on physical activity was published. Physical activity recommendations included '30 minutes of moderate intensity physical activity on at least five days of the week' and for those already doing some vigorous intensity physical activity 'three periods per week of vigorous intensity physical activity, of 20 minutes each' (Milton and Bauman, 2015). These physical activity guidelines were similar, but not identical to recommendations in the ACSM and Centre for Disease Control and Prevention in the United stated of America. In 2008 the Department of Health in England commissioned a review of the guidelines and in 2011, the guidelines were modified, these guidelines stated.

"Adults should aim to be active daily. Over a week, activity should add up to at least 150 minutes (21⁄2 hours) of moderate-intensity activity in bouts of 10 minutes or more – one way to approach this is to do 30 minutes on at least 5 days a week. Alternatively, comparable benefits can be achieved through 75 minutes of vigorous-intensity activity spread across the week or a combination of moderate and vigorous intensity activity" (gov.uk., 2019).

In light of new evidence, current guidelines have removed the minimum bout requirement and thus the current guidelines present themselves as 150 minutes of moderate intensity can be accumulated in bouts of any length (UK CMO, 2019), while the inclusion of two resistance session a week has also been included (nhs.uk, 2022). However, there is little evidence to suggest these guidelines are improving physical activity outcomes and the subjective nature of physical activity guidelines might not be helping people's ability to self-monitor physical activity.

One particular method that may aid overcoming these barriers and employed by Larsen et al. (2017) was to demonstrate MPA with a 10-minute treadmill bout immediately prior to completing physical activity recall. Although their results were insignificant, participants who had completed a demonstration recalled performing less MPA. It is highly likely that those who did not complete the MPA demonstration were unfamiliar with the required walking speed to meet MPA, whereas those who completed the demonstration had anchored the subjective feeling of MPA and were therefore able to identify the correct intensity more easily. However, participants who completed the demonstration reported significantly fewer minutes of MPA than those who did not. When comparing the correlation between objectively measured and self-reported MVPA, the control group had very little ability to identify MPA (r=0.05), compared with the intervention group, who although slightly outperformed the control group still struggled to identify MPA (r=0.28). It would therefore seem, even when MVPA has been demonstrated, an individual's ability to correctly identify MVPA does not correlate strongly to objectively measures physical activity. Similar responses have been reported when active demonstrations are used. Rice et al. (2008) compared giving participants a written description of MVPA guidelines vs a 10-minute treadmill demonstration at 55-70% HR_{max}. Those participants who had been given the demonstration were more able to correctly identify MVPA one month later. The authors reported the limitations in moderate intensity identification could be due to understanding physical activity guidelines. It has previously been reported that adults find the guidelines misleading and confusing, specifically the intensity, duration, and frequency required (Morrow et al., 1999). What appears to be clear is that subjective measures of physical activity are interpreted differently among populations. Wide variance in its application is common, while participants' ability to successfully meet intensity threshold cut points, based on physical activity guidelines, could be contributing to the lack of physical activity being performed. It would therefore seem, that exercise guidelines require attention, one method that could potentially improve this is using objectively measured physical activity.

2.12 Objective measures of physical activity - pedometers/accelerometers

Pedometers have long been used as a method for tracking steps and activity (Bassett et al., 2017). They are low-cost devices that measure steps taken through the repetitive, rhythmic locomotive action of leg and arm swing movement associated with walking gait cycles. Exercise guidelines have been designed to incorporate these tools, with step accumulation of 10,000 steps·day^{-1} often referred to as the standardised goal of daily activity (Tudor – Locke *et al.,* 2011). Accelerometers allow for more in-depth analysis of movement, gauging the speed or acceleration of force, and can measure not only total step accumulation but the time in which those steps were taken, allowing for the identification of walking speed and cadence, and thus absolute intensity.

A handful of authors have used pedometer and/or accelerometer interventions to investigate whether they have the potential to increase daily physical activity (Bouchard et al., 2013; Barreira et al., 2016) with conflicting findings. Reasons for this could be the lack of user / technology interaction between participant and device as they lack the ability to guide the user in real time to a walking speed that meets moderate intensity thresholds. Slaght et al. (2017) investigated whether devices that have the potential to increase cadence and thus walking intensity through live digital feedback are effective at increasing physical activity. Participants were divided into two subgroups over a 12-week intervention period. Initially, participants completed phase one where all participants wore unlocked pedometers and were instructed to perform a minimum of 150 minutes of MPA per week. In the second phase, groups were randomly assigned to either continuing 150 minutes of MPA per week (control), or, received individualised walking cadence prescription (40% VO_2R) with a programmed pedometer that gave instant visual feedback for every 10 minutes of MPA completed (intervention). At baseline, all participants, irrespective of intervention branch, completed a mean (SD) of 100 (61) min·wk^{-1} of MPA. Phase one significantly increased total MPA to a mean (SD) of 117 (64) min·wk^{-1}. In phase two the control group's MPA reduced to a mean (SD) of 88 (71) min·wk^{-1} from baseline, while the intervention group significantly increased their total MPA to a mean (SD) of 203 (91) $min \cdot wk^{-1}$. The results demonstrate, at least in the short-term, that providing people with real-time objective feedback on their relative intensity increases their MPA. The large difference in MPA between control and intervention between weeks 6 -12 was likely associated with the tailored approach to physical activity the intervention group received. Additionally, the visual feedback received for each bout of MVPA completed could have increased exercise adherence, compared to the intervention group. The study does have limitations, including a small sample size which is likely to increase the uncertainty of the population effect size estimation. This type of technological interaction has been associated with increased activity by a number of authors (Bravata et al., 2007; Bouchard et al., 2013; Marshall et al., 2013) and demonstrates the potential benefit of visual feedback, as well as reinforcing positive behaviour in increasing physical activity adherence. The reduction in MPA observed in the control group between weeks 6 -12 may also highlight potential weaknesses in exercise prescription and its sustainability. MPA not only decreased, but the control group performed less MVPA in week 12 than at baseline. This reduction in MVPA may highlight the need for change in exercise prescription, continual interaction, and positive reinforcement of behaviour to reduce tedium and increase exercise adherence.

2.13 Wearable technology

Wearable technology is defined as any type of technological device that has been designed to be worn on the user’s body. This can be in the form of jewellery, accessories, clothing, and elements of clothing. Common, traditional wearable devices such as the pedometer or accelerometer often have no screen on the device, do not have the ability to notify the user via sound or haptic nudges, and have little to no user interaction. Modern wearable devices such as the Apple Watch, on the other hand can interact with the user in many ways. The Apple Watch has the capacity to give the user live information during physical activity, such as time spent exercising, number of calories consumed, total distance, and current heart rate. They also have the capacity to notify the user, via nudges, to guide physical activity intensity and have a similar user interaction as a mobile phone device for example, allowing for calls, messaging, and emails to be answered via the wearable device itself. Developments in wearable devices offer a new opportunity to change physical activity prescription, adherence, and behaviour. Sales of smart watch devices has seen exponential growth in the last five years and is expected to reach 253 million units sold in 2025 (Statista, 2023). Wearable devices offer a multitude of behavioural change techniques that can be used to promote physical activity behaviour (Sanders et al., 2016) and aid the user in improving their general health. Recent research (Lehrer et al., 2021) has identified four wearable use patterns that bring about different behavioural outcomes, these are, 1) following – following leadership strategies provided by the wearable and the outcome of compliance change. 2) Ignoring – ignoring leadership strategies provided by the wearable and the outcome of no behaviour change. 3) Combining – combining leadership strategies by the wearable with self-leadership strategies. 4) Self – leadership – supported by the wearable, and the outcome of no wearable induced behaviour change. These tools use a range of persuasive methods and social influence strategies to increase user interaction. Gamification is used at several different levels, creating competition and challenges, both at an individual and social level, which is further increased with virtual reward systems for achievement or 'winning' competitions. In some cases, physical rewards are applicable with discounts off experiences or products. A recent review suggested three key gamification themes were linked to increased physical activity, goal based, social based, and rewards-based gamification (Cho, Kaplanidou and Sato, 2021). The publication of activity information between social groups utilises social influence principles (Stragier, Evens and Mechant, 2015), and its popularity is growing in those interested in quantifying their behaviour, a self-discovery via personal analysis (Swan, 2009; Piwek et al., 2016).

A recent meta-analysis (Gal et al., 2018) investigated the effectiveness of wearables and smartphone applications for promoting physical activity. Effectiveness was defined as the ability of the smartphone or wearable device app to increase physical activity. Eighteen RCTs were included. The results indicated a small to moderate (point estimate Cohen's d = 0.43 [95%CI: 0.03 to 0.82]) increase in physical activity. More specifically, there was an increase in completed minutes of physical activity per day and a moderate increase in daily step count (point estimate Cohen's d = 0.51 [95%CI: 0.12 to 0.91]) which were attributed to device-lead interventions in all 18 RCTs. However, activity was measured using either a pedometer (N=2), accelerometer (N=9), smartphone-based app (N=3), or subjectively (self-reported) (N=4). The development of devices such as the Apple Watch, Fitbit and Samsung Gear watches has made physical activity analysis, the 'quantification of oneself' (Swan, 2009; Almalki, Gray and Sanchez, 2015) more accessible to the mass market, the devices used in the RCT's highlighted by Gal *et al.* (2018) are devices that likely had no user interaction and do not have a screen that gives live feedback to the user as they are exercising. Additionally, whilst the authors reported small to moderate increases in physical activity, the level of uncertainty spans form trivial to large, so the true effect wearable devices have on physical activity completion could well be much greater or trivial. Since the publication of the meta-analysis (Gal et al., 2018), features have been added to wearable devices that might increase physical activity, including 'nudges' designed to encourage or remind the user to move. Nudge theory was named and popularised by Leonard, (2008) and outlines nudges as a concept that focuses on humans' ability to make decision instinctively, and how nudges can be used to encourage change management, motivation, leadership and coaching. However, not all authors agree that wearable devices and nudges are useful in developing physical activity understanding, Toner, (2018) believes that prolonged use of such devices may in some cases normalise the embodied subject and cause an anesthetisation of human experience when performing physical activity. Toner perceives self-trackers to encourage users to consider bodily function in quantifiable terms, reducing subjective feeling and paying less attention to the embodied sensations that accompany physical activity, which may hinder enjoyment. Additionally, not all authors advocate the use of nudge theory, there are some ethical concerns regarding the increased autonomy these technologies offer (Owens and Cribb, 2019), which may increase the risk of burden anxiety as wearable technology fails to support autonomous decision making. Autonomous decision making refers to the process of psychological deliberation, instead risking the process of genuine autonomous deliberation. Whether this method of inducing or highlighting the need for more physical activity is beneficial, is questionable and current research has shown conflicting evidence (Marteau et al., 2011; Weinmann, Schneider and Brocke, 2016; Whelan et al., 2017) for the efficacy of nudge theory in promoting physical activity.

In its simplistic form, most wearable devices have the ability to track and record heart rate with relative accuracy especially at moderate intensity (Khushhal et al., 2017; Abt, Bray and Benson, 2018; Johnston et al., 2020). The development in photoplethysmography (PPG) technology used to measure blood flow change, and subsequently heart rate, has allowed the general population access to this data, who now can track their heart rate continuously throughout daily activities and exercise. This means anyone who has a wearable device now has the capacity to measure relative intensity physical activity. In addition to this, the Apple Watch, the most popular wearable on the market (Statista, 2022a) now has the ability to obtain physiological data including VO_{2max}, blood oxygen saturation, and electrocardiogram (apple.com/uk, 2023) offering an abundance of data to an ever-growing set of tools for the quantification of one's self.

Developments in wearable technology have now granted access to individualised data and subsequent measurement of relative intensity physical activity to the mass population. Physical activity intensity, dose and duration play a critical role in improving CRF, while a balancing act between these variables and physical activity behaviour impact the sustainability of long-term adherence. Arguably, the most difficult variable to control in long term adherence to physical activity, is intensity. Gauging this accurately is important for improving CRF but may also improve sustainability as people perceive moderate intensity to be of greater enjoyment compared with vigorous and high intensity physical activity (Ekkekakis and Biddle, 2023). While it is still unclear whether exercising at a lower intensity stimulates the cardiorespiratory system sufficiently enough to reduce all-cause mortality and improve CRF (Yu et al., 2003; del Pozo Cruz et al., 2021), the 'sweet spot' whereby enjoyment is high (Zenko, Ekkekakis and Ariely, 2016) and CRF is improved, is likely to be moderate intensity. Walking is the most common form of physical activity performed at a population level (Sport England, 2020), developing methods to guide people to a physical activity intensity that promotes CRF on a mass scale (i.e., moderate intensity walking) is of benefit, not only to the population, but to health services, and a number of socioeconomic factors that may reduce the burden of co-morbidities and all-cause mortality associated with a lack of physical activity. Therefore, further investigation into wearable technology, and moderate, relative intensity is warranted.

3. General Methods

3.1 Quantitative studies

The purpose of this chapter is to provide an outline of the general methods that have been used across all quantitative trials conducted in this thesis. This includes a description and justification of each procedure and how it has been used.

3.1.1 Ethical Considerations

Institutional ethics approval was obtained for all studies from the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull (REF – FHS230). Prior to study commencement, all participants were provided with a written participant information document highlighting testing procedures, the benefits and risks of each study, and information on their right to withdraw. Following a sufficient period to consider participation, to ask questions, and outline any areas for further discussion, participants provided written informed consent.

In accordance with University of Hull guidelines, all participants completed a health screening protocol and subsequent questionnaire prior to commencement of the study. Participants with any medical conditions were required to present medication prior to exercise (e.g., participants with asthma were required to have their inhaler present, any participants with contraindications to exercise highlighted through the screening process, were excluded). On each subsequent visit to the laboratory participants also completed a pre-screening assessment. This involved making sure there had been no developments in injury or subsequent contraindications to health. If there had been any subsequent changes to participant health, exercise was not permitted, and the participant was advised to seek medical clearance before any further participation.

3.1.2 Participant recruitment

Participants were recruited from the local population in Hull, the East Riding of Yorkshire, and the University staff and student community. Participants were contacted or made aware of the opportunity to participate in studies using social media, poster advertisement, word of mouth, and the university portal and internal emailing.

3.1.3 Participants

Healthy adults aged 18-59 years old were recruited to participate in each study. Elite athlete populations, and/or those with prior experience in speed walking or race walking were excluded from testing protocols. This was due to the nature of cadence cueing in the study protocol, and the potential for this level of experience to cause a training effect.

3.1.4 Pre – Experimental Procedures

Before each experimental trial participants were asked to adhere to a standardised procedure to limit confounding variables that may affect physiological response to exercise. Prior to each trial participants were required to abstain from alcohol consumption for 12-hours (Rosenberg and Durnin, 1978; Westerterp-Plantenga et al., 2006) and abstain from caffeine consumption 8 hours prior. Each experimental trial was conducted at a similar time of day to account for the influence of circadian rhythm and its potential effect on heart rate (Reilly, 1990). Participants were also instructed to avoid strenuous exercise in the 24 hours preceding each visit.

3.1.5 Familiarisation Trials

All participants were familiarised with all testing procedures and equipment prior to the commencement of the first trial to minimise both learning and anxiety effects. This involved familiarisation with walking on a treadmill, performing on-and-off movements to familiarise participants with the safest approach to disembarking the treadmill and the fitting of the face mask (Hans Rudolph, USA) for the gas metalyser (Metamax 3B, Cortex, Liepzig, Germany).

3.1.6 Novel 'MVPA' Apple Watch app

The MVPA app was designed and developed by this research group from inception. The app build was externally completed by BetaJester Ltd.

3.1.6.1 Heart Rate Reserve

The MVPA Apple Watch app was designed to quantify MVPA and to overcome the barriers and limitations of the Apple Watch Activity app. Previous studies have indicated that the Apple Watch Activity app underestimates the intensity required to achieve MVPA by ~25% when compared to directly measured %VO_2R (Khushhal et al., 2017; Abt et al., 2019). The MVPA app has been designed to overcome this limitation, using HRR to quantify moderate intensity. The MVPA app uses %HRR because it has been reported to be similar to %VO_2R (Swain and Leutholtz, 1997), and %HRR can be easily calculated by the Apple watch user using data already available to them (resting HR and estimated maximal heart rate). A fifth generation Apple Watch (Series 5) running watchOS 7.1.1, or later update was used to determine moderate intensity exercise. The MVPA app used the ACSM definition of moderate intensity, defined as 40% to 59% of HRR or VO_2R (Riebe, 2018). As VO_2R data is not available through the Watch PPG sensor, HRR was used to substitute for this, such that moderate intensity physical activity was defined as 40 – 59% HRR. The equation used to calculate moderate intensity within the MVPA app was:

$$\textit{Target HRR} = (HR_{MAX} - HR_{REST}) \times \textit{exercise intensity (e.g., 0.4)} + HR_{REST}.$$

Maximal heart rate was estimated using the formula:

$$HR_{MAX} = 206.9 - (0.67 \times age)$$

(Gellish et al., 2007).

Resting heart rate was taken from historic values stored in the Apple Watch health app. Values up to 7-days prior to laboratory trials were used to calculate a mean resting heart rate. The Apple Watch can record resting heart rate when the user is in prolonged sedentary positions, hence participants wore the Apple Watch for a minimum of 7 days prior to laboratory testing. Additionally, a resting heart rate protocol was created within the MVPA app which allowed for direct measurement of resting heart rate. The protocol involved recording the heart rate for 5-minutes and was used in the resting VO_2 laboratory protocol described in more detail in this chapter.

3.1.6.2 Walking cadence

Walking cadence target was presented to the user in number format on the Watch screen. The measurement frequency was set to 0.2 Hz (once every 5 s). Cadence cueing, through haptic or auditory feedback (metronome) was used to guide users to the correct cadence during overground walking trials, which is explained in more detail later in this chapter. Feedback was administered on the measurement of mean cadence and %HRR. If %HRR was not greater than 40%, cues increased in frequency to that which was predicted to result in the %HRR reaching >40%. This was continually monitored and modified every 30 seconds via the Watch until 40% HRR was obtained. If %HRR was above 40% then the cue remained at the frequency when >40% HRR was first achieved. If %HRR exceeded 45% the cue would reduce to a rate predicted to achieve 40-45% HRR.

Figure 3.1 An illustration of the Watch interface during physical activity, information available on screen in walking mode.

3.1.6.3 MVPA activity log

Every second spent at an intensity at or above 40% HRR counted towards the accumulation of an MVPA minute. The accumulated total was displayed on the Apple Watch MVPA app interface and on the companion iPhone app.

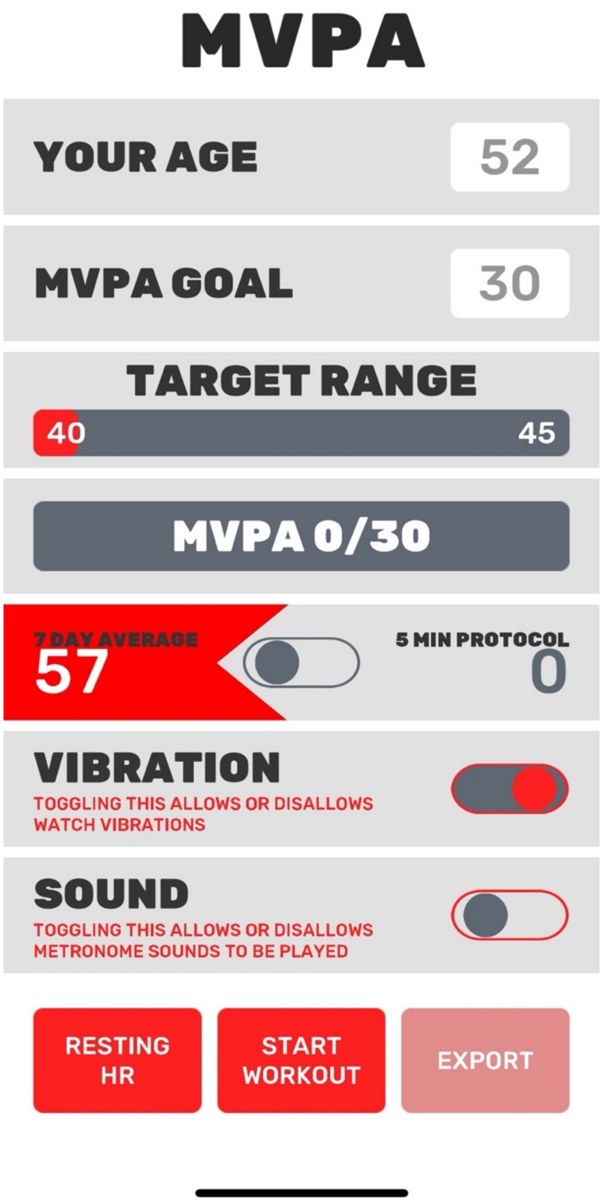

Figure 3.2 interface for the MVPA companion iPhone app

3.1.6.4 MVPA app algorithm

For the MVPA app to calculate the required tick rate to initially guide users to the required intensity, it used the following equation:

TickRate (Target Metronome) = (1/ ((Target HRR)/ ((Resting HRR) x (Constant Multiplier Value)))) ^ 1/ (Constant Power Value)

This works on the basis that to achieve the required target HRR, the tick rate needs to be administered and thus calculated. This is completed by inverting the estimate equation, which demonstrates a linear relationship between walking speed and intensity (%HRR). From this, required walking cadence can initially be estimated and the preliminary tick rate is produced. The equation multiplies resting heart rate by a constant value based on the linear relationship between heart rate and walking speed, then divides heart rate by the result, to obtain a relative individualised value. This value is then inverted, by dividing one by the number, and expressed to the power of 1 over a constant value, chosen based on projected data derived from the walking speed to heart rate relationship. Heart rate data are then collated as the MVPA app is in use and a walking speed / %HRR relationship is individualised to the user and adjusted over time based on more accurate individualised relative data to accurately produce an individualised tick rate that corresponds to 40% HRR.

3.1.7 Experimental trials

3.1.7.1 Resting VO_2 and resting heart rate

On entering the laboratory, stretch stature was measured using a wall mounted stadiometer (Holtain Ltd, Dyfed, Wales, UK) and nude body mass (WB-100MA mark 3, Tanita corporation, Tokyo, Japan) obtained. Participants were then placed in a supine position on a massage bed with a cushion placed beneath the head for 30-minutes. Breath by breath expired air was collected (Metamax 3B, Cortex, Liepzig, Germany) throughout this period. The analyser was calibrated to manufacturers guidelines using room temperature, air, and a known concentration of oxygen and carbon dioxide. Volume was calibrated using a 3-litre syringe. Although we are not aware of any standardised method for measuring resting VO_2 for the purpose of calculating VO_2R, we developed our methods based on that reported by (Miller et al., 2012) and previously used by this research group (Abt, Bray and Benson, 2018; Abt et al., 2019).

The first five minutes of breath-by-breath data was discarded to allow for habituation. The final five-minutes of data were also discarded to allow for expectation effects. Resting VO_2 was defined as the remaining 20-minute average. Between minutes 15 and 20 of the protocol, the MVPA app's resting heart rate protocol was initiated to obtain a five-minute Watch sampled resting heart rate. This measure was taken to explore the usefulness of a practical resting HR protocol that could be used by the public, given that the 30-minute protocol is unlikely to be widely adopted by Apple Watch users.

Resting heart rate was also recorded using a Polar chest strap (Polar T31, Polar Electro, OY, Finland) and defined as the mean heart rate recorded between minutes 5 and 25 in line with the resting VO_2 sampling process. Throughout the protocol laboratory lights were turned off and all other laboratory activity ceased. Participants were instructed, prior to the protocol commencement, to relax as much as possible but avoid going to sleep.

3.1.7.2 7-day resting heart rate

Participants were provided with an Apple Watch Series 5 (watchOS 7.1.1 or later) paired to either their own personal Apple iPhone running iOS 13 or later, or were provided with an Apple iPhone SE if they did not own one. Participants were required to wear the Apple Watch for a minimum of 7 days prior to the second laboratory visit. Participants were required to wear the Watch for a minimum of 10 hours per day, which was monitored and recorded via the 'stand' ring in the Apple Watch Activity app. The MVPA app sourced the 7-day resting heart rate data stored in the Health app (Apple, 2022) to calculate mean resting heart rate, with this RHR mean used to calculate %HRR in the MVPA app.

3.1.7.3 Determining VO_{2peak}

All participants completed a graded incremental test to volitional exhaustion to determine the peak oxygen uptake and maximum heart rate. The protocol was performed on a motorised treadmill (H-P Cosmos, Germany) commencing at a speed of 3.0 $km \cdot h^{-1}$ and a gradient of 1%. Speed was increased by 1.0 $km \cdot h^{-1}$ every minute until running form was deemed to be inhibited by running speed, at which point gradient was subsequently increased by 1% every minute until volitional exhaustion was achieved. Data were analysed using 10 s means with VO_{2peak} determined as the highest 30 s mean of VO_2 obtained during the trial.

3.1.7.4 Determining %VO_2R

For the purposes of calculating %VO_2R a protocol previously used by this research group (Abt et al., 2019) was used and calculated as follows:

$$\%VO_2R = (VO_2 - \text{Resting } VO_2) / (VO_{2MAX} - \text{Resting } VO_2) \times 100$$

3.1.7.5 Trials to compare MVPA app vs the native app

The methods were developed from a previous research investigation (Abt, Bray and Benson, 2018). Participants completed a series of 5-minute walking bouts on a motorised treadmill (H-P Cosmos, Germany), at a gradient of 1%, in a temperature-controlled laboratory. Each walking bout was followed by a 5-minute bout of seated rest. The treadmill speed started at 3.5 $km \cdot h^{-1}$ and each subsequent bout increased by 0.5 $km \cdot h^{-1}$. Participants continued to exercise until three of the 5-minutes met the MVPA app's criterion moderate intensity of 40% HRR and all 5-minutes were indicated as meeting the intensity requirements to advance the green 'exercise' ring in the native Apple Watch Activity app. The time duration differences between the MVPA app and native app are due to the delayed physiological response of heart rate during exercise (MVPA app) compared to the instantaneous response of a triaxial accelerometer (native Activity app) once movement has commenced. During each 5-minute period of exercise, oxygen consumption, heart rate using the MVPA app, and a polar strap (Polar T31, Polar Electro, OY, Finland) were recorded. Cadence was recorded through the MVPA watch app by accessing data stored in the iPhone Health app. Additionally, RPE, thermal sensation, and breathlessness were recorded at each stage (see

Appendix C), and a talk test (Shafer et al., 2000) was performed in the third minute of each stage followed by the question *'Could you perform the talk test with ease?'* which had to be answered yes or no by participants. Participants were instructed to maintain their normal gait and were not permitted to hold the treadmill handrails. At termination of each 5-minute stage participants straddled the treadmill and once the belt speed had become stationary, a chair was placed on the treadmill and participants instructed to sit. Participants were instructed to sit with no movement, to avoid contributing to the Apple Watch green 'exercise' ring with any hand movement. RPE, breathlessness, and thermal sensation were used to determine participants ability to correctly identify moderate intensity based on NHS guidelines. NHS defines subjective moderate intensity physical activity as:

'*Moderate activity will **raise your heart rate**, and make you **breathe faster** and **feel warmer**. One way to tell if you're working at a moderate intensity level is if you can **still talk but not sing**.'*

Participants ability to correctly identify thermal sensation, breathlessness, and RPE in accordance with moderate intensity was linked with the actual time spent in moderate intensity according to breath-by-breath analysis (40-59% VO_2R). For every correct identification of breathlessness (a rating of 3), thermal sensation (rating of 8), and RPE (rating of 3) was deemed as correctly identifying moderate intensity if the corresponding VO_2R was between 40-59%.

3.1.7.6 Apple Watch Cadence cueing

Participants completed three 10-minute over-ground trials in an indoor laboratory. Trials were conducted on a 60 m figure-of-8 track installed on a flat, level surface in a temperature-controlled laboratory. Participants initially completed a 10-minute self-paced moderate intensity walking trial directed by NHS guidelines, described to the participants as follows:

'*You should aim to walk at a moderate intensity. The way the NHS describe moderate intensity is exercise that raises your heart rate, makes you breathe faster and feel warmer. One way to tell if you're working at a moderate intensity level is if you can still talk but not sing.'*

(nhs.uk, 2022)

Participants were initially randomly assigned to one of two cadence cue trials, either: (1) a metronome, or (2) haptic feedback, with both administered via the MVPA app. For both trials, participants were guided to a cadence that was predicted to elicit 40% HRR, with the Watch administering either one haptic feedback administered through the Watch haptic engine or metronome cues administered via Bluetooth headphones. Cues were administered for every other step – that is, if a participant's minimum MVPA intensity was calculated to be reached at 140 steps·min^{-1} the MVPA app would administer 70 metronome or haptic feedback cues per minute. Participants were instructed to synchronise either their left or right foot contact with the cue. Heart rate was recorded through the MVPA app. The speed of cues was amended dependent on %HRR. If a participant's %HRR was not meeting the criterion lower bound of moderate intensity (40%), then the cadence cue would increase until the criterion moderate intensity was met. Exercise intensity was determined using the

HRR equation from the ACSM guidelines (Liguori, 2022) for moderate intensity physical activity 40 – 59% VO_2R (Blair *et al.,* 1991) outlined in section 3.1.6.1.

Participants were instructed to align their walking cadence to the cue as accurately as possible and maintain a normal walking cadence. Walking cadence was recorded using the Apple Watch and video analysis was used to record each trial in line with reported best practice (Johnston et al., 2020). A reviewer analysed the recordings for cadence once all trials had been completed by counting steps completed in each minute. Minute one and minute 10 were discarded from the video analysis, ensuring eight minutes of the bout were analysed.

3.2 Qualitative study

The purpose of this section is to provide an outline of the two qualitative studies design, the researchers philosophical paradigm, and procedures used throughout. As is customary in reporting qualitative research, some of this section is written in the first person. As is explained in greater detail within this section, the decision to undertake qualitative research is influenced by the researcher's position and assumptions and thus requires recognition as influential, and has implications within the research process (Collins and Stockton, 2018). This section highlights key decisions in the design, collection, and analysis of the qualitative research conducted.

3.2.1 Ethical Considerations

See section 3.1.1 for the general ethics statement, which also relates to the qualitative studies. Specific to the qualitative studies, an additional consideration was that prior to commencement of the audio recording, participants provided verbal consent for the interview to be recorded, transcribed, and analysed.

3.2.2 Philosophical paradigm

As the researcher is an integral component of the research process and findings in qualitative research, it is critical to the analysis to highlight the researchers' values and experiences that shape their approach to research (Clarke and Braun, 2013). It is also necessary to understand the researcher's worldview to enable comparative conclusions to be drawn against theoretical paradigms and how this may impact the data collection and analysis process. A researcher's world view is influenced by racial, class, gender, cultural, and community perspectives with which the researcher has been influenced (Denzin and Lincoln, 2011). The choice of topic, data collection process, and the analytical process are all affected by the researcher's experiences, values, opinions, and intentions (Clarke and Braun, 2013). It is therefore of significance that the researcher highlights their background, beliefs, and outlines potential biases that may impact the research. Reflexivity is a central matter in all stages of qualitative research (Clarke and Braun, 2013; Berger, 2015), and is defined as a process of reflection that allows the researcher to self-evaluate on values and behaviours that impact on the research process, and forms a broader debate about ontological, epistemological, and axiological components of the self and self-knowledge (Berger, 2015).

3.2.3 Researcher background

I'm a 32-year-old white, British male PhD student in Sport, Health and Exercise Science. I have an MSc Sport Science, and a BSc (Hons) Sport, Health and Exercise Science. I have worked as a laboratory technician in sport science departments at two other English university institutions, and throughout my educational process have held part time jobs as a gym instructor, which included working with clients who have been referred for exercise by their GP for health reasons. During the first 3 and a half years I worked as a freelance tutor alongside my PhD, delivering gym instructing and personal training qualifications. In my final year I worked in a full-time academic post as a lecturer in another UK institution. Prior to my PhD I had no qualitative research experience but had completed quantitative research as part of my MSc qualification and several peer review publications within the field of sport science. I have a keen interest in physical activity and have always been extremely active.

3.2.4 Philosophical positioning

As a novice qualitative researcher with more experience in quantitative research, there is an element of positivism within the field's approach to empirical scientific evidence. Prior to completing this qualitative study, I had not considered in enough detail the impact a researcher may have on data collection and analysis. Reading post positivism literature has highlighted the need to expand my thinking beyond these assumptions and understand that as a researcher I'm an integral component of the research and it is extremely difficult to eliminate completely all elements of bias from the research design, data, and findings. Moreover, the concept of truth may be a fluid concept, more so than a positivist approach allows for. In certain circumstances I can appreciate a socially constructed reality may exist, as humans' conception of social reality is shaped in ways that make it fluid and multifaceted, and that the mind plays a foundational role in shaping reality on an individual basis, giving meaning to objects and how interpretation of movement and utterances of other people, exists to create a reality (Sparkes and Smith, 2013). The combination of my background in sport science research with an empirical approach and wider reading as part of this study design would lead to a post positivist approach to answer appropriate research questions, but with an understanding that multiple realities may exist within social construes.

The purpose of the first qualitative study was to understand participant perceptions of exercise guidelines. With a post positivist approach, the philosophical stance is described below:

Ontological stance – A reality exists but not in a perfect form, and that this reality is drawn from an understanding and definition of reality.

Epistemological stance – A social reality exists from human conjecture but has enough stability and patterning to be known.

Axiological stance – As much as possible, all inquiries should aim to be free of bias, the researchers should utilise scientific methodology for gathering data and achieve as close as possible, neutrality during the inquiry process.

3.2.5 Data management

The key features of the data management plan are highlighted:

Hard data – Personal data and participant consent forms were stored in paper format in a locked draw, which only the lead investigator had access to. The locked draw was in a locked office on the University of Hull campus.

Audio data – Audio recordings were captured on an iPhone with face recognition and pin code locking facilities. The recordings were immediately transferred to a MacBook laptop which was also password encrypted, and a back-up copy was stored on a password encrypted hard drive.

Digital data – Anonymised transcripts stored as Word documents on the same password encrypted MacBook and hard drive were accessible to the lead and principal investigators. Files were also stored on the University approved online Box file storage system accessed by the lead and principal investigator. Analytical writing was anonymous and stored on the University approved Box storage system, and on password encrypted MacBook and hard drive belonging to the lead investigator.

3.2.6 Data collection

Semi structured interviews were used as part of the data collection process to allow individual participants to give answers that they may not have shared in more social constructs. Although the interview process was not expected to raise sensitive or intimate issues, allowing individual participants the opportunity to speak on a one-to-one basis meant that a true understanding of the research topic was enabled. Questions surrounding subjective perception were asked, therefore obtaining the individual's perspective on those guidelines was critical for the data collection process. For ease and to reduce the number of visits participants had to complete, interviews were conducted as the final part of each participant's 3rd visit to the lab. All interviews were conducted on the University of Hull's campus within the Sport, Health and Exercise Science department in a room offset from the main biomechanics' lab. All interviews were audio recorded using the voice memos app on an Apple iPhone and recorded in MP3 format. On completion, all audio files were stored on a password encrypted MacBook laptop ready for transcription. Transcription was completed in Microsoft Word using the transcription tool and checked and modified accordingly by the lead investigator. All participants who completed the physical trials were asked to complete the semi structured interviews, seven participants requested not to take part, meaning 67 participants completed the semi structured interviews. Interviews were analysed until thematic saturation, which is the point at which no new themes or codes were identified in the data and a persistent repetition was observed between interviews (Saunders et al., 2018) 23 participants transcripts were analysed.

3.2.7 Data analysis

Once transcription was completed, coding was enabled and completed in Microsoft Word using a thematic analysis (Braun and Clarke, 2006). Initially a deductive approach was applied for the thematic analysis, as the theoretical framework and design of the semi-structured interview allowed for some preconceived themes to be hypothesised. Specifically, due to the subjective nature of physical activity guidelines, and knowledge surrounding the variance between objectively measured physical activity compared to subjectively measured physical activity (Colley et al., 2018), it was inherent there would be a level of subjectivity and confusion surrounding participants' perception of government guidelines. Therefore, a semantic approach was used, analysing the explicit content of the data. The analysis followed the six-step process (Braun and Clarke, 2006) highlighted below:

Stage 1: Data familiarisation – Immersion into the data to become familiar with the depth and breadth of the content. Immersion involved repeated reading of the data, searching for meaning and patterns.

Stage 2: Generating initial codes – Once a list of ideas had been formulated, the production of initial codes was generated, identifying features of the data that appeared interesting or of significance. As a deductive approach was used, data were approached with specific questions that required answering and that were to be associated with specific codes.

Stage 3: Searching for themes – Once all the data had been coded and collated, a broader level of themes was applied to the code. This involved arranging all relevant coded data extracts within the identified themes in a bid to re-focus the analysis at a broader level. Themes were then collected into candidate themes, which contain sub-themes.

Stage 4: Reviewing themes – Once candidate themes had been devised, a process of refinement was applied. A two-step review process was used. Step one involved reviewing coded data extracts and consideration as to whether the themes formed a coherent pattern. Step two reviewed the candidate themes, whether the data extracts within it fit, or whether the candidate themes themselves were problematic. This process included reworking themes where possible or creating a new theme to amalgamate existing extracts that did not fit their current existing theme or discarding them from the analysis. Once satisfied the candidate themes adequately captured the contours of the coded data, a thematic map was created. This process was then applied to the entire data set. Consideration was given towards the validity of individual themes in relation to the data set and whether the thematic map accurately reflected the meanings evident in the data set as a whole.

Stage 5: Defining and naming themes – Once a thematic map had been satisfactorily developed, themes were refined and defined that were presented in the analysis. Identification of the 'essence' of what each theme is about, as well as the themes overall and determining what aspect of the data each theme captured, identifying what is of interest and why. Each theme was then analysed in detail, identifying the story each theme told, and how this fits the overall dataset in relation to the research question.

Stage 6: Producing the report – Once themes had been fully developed, the final analysis and write up of the report was conducted. The analysis needed to portray complicated data in a valid and convincing manner to the reader, providing a concise, coherent, logical, and non-repetitive account within and across themes.

4. Agreement and relationship between measures of absolute and relative intensity during walking: A systematic review with meta-regression

4.1 Introduction

Walking is a very popular form of physical activity at a population level (Grigoletto et al., 2021). It is low cost, accessible, and well-tolerated across age groups (Roberts, Townsend and Foster, 2016). Given this popularity, walking is a key intervention for physical activity promotion (Foster et al., 2018a). Advocating walking (and physical activity in general) is important because it is well documented that physical activity reduces the risk of developing a range of chronic diseases(Lee et al., 2014; Barengo et al., 2017). For example, current National Health Service (NHS) guidelines in the United Kingdom recommend that people should accumulate a minimum of 150 minutes of moderate-intensity or 75 minutes of vigorous-intensity physical activity per week (Sport England, 2019). Physical activity guidelines like these are common across many countries (Brown et al., 2022; Thomas et al., 2022), and the importance of meeting them is well established (Allender et al., 2007; Kraus et al., 2019; Silva et al., 2020; Mañas et al., 2021). Moreover, evidence suggests a dose-response relationship between physical activity and reduced risk of all-cause mortality (Hamer, de Oliveira and Demakakos, 2014; Lee et al., 2019). Accumulating a sufficient dose of physical activity is therefore important. Although emerging evidence suggests that low intensity physical activity may also reduce all-cause mortality (del Pozo Cruz et al., 2021), nearly all current physical activity guidelines refer to moderate intensity as the minimum requirement.

Although physical activity guidelines are not always designed to be public facing, those that are and that attempt to describe how moderate intensity can be regulated (or is perceived) by people under free-living conditions are subjective and could even be considered vague. For example, the NHS guidelines suggest that moderate intensity is associated with "a feeling of being warm, elevated heart rate and breathing, and the ability to talk but not sing" (nhs.uk, n.d.). This guidance is clearly subjective and open to individualised interpretation (Knox et al., 2013). The language used in physical activity guidelines has also been reported to be inaccessible (Nobles et al., 2020) and difficult to interpret by the general public (Essery et al., 2020).

Given the ambiguity and subjectiveness of these physical activity guidelines, a key question is how physical activity and exercise intensity (referred to as intensity from now on) can be measured objectively. Generally, objective intensity can be measured via absolute or relative methods. Absolute intensity is a measure unrelated to the individual's cardiorespiratory fitness and is often measured via an accelerometer (Watson et al., 2014). Relative intensity is a measure that is proportional to the cardiorespiratory fitness of the individual, and usually involves the measurement of heart rate or oxygen consumption. One of the most common absolute methods of objectively quantifying intensity is the metabolic equivalent (METs), which is a ratio of the metabolic cost induced by different types of exercise and intensity compared to the metabolic cost of sitting quietly (Freedson, Melanson and Sirard, 1998). The ability of METs to quantify intensity across a spectrum of physical activity, to a wide range of the population, has ensured its popularity among researchers and health and fitness professionals. For example, a walking cadence of 100 steps·min^{-1} has been recommended as sufficient to achieve moderate intensity walking as determined by a threshold of 3 METs (Tudor-Locke et al., 2019).

There is, however, growing interest in relative methods of measuring intensity, allowing for more accurate, inter-individual prescription (Abt et al., 2019). A relative method of measuring intensity is one that relates to one or more physiological characteristics of the individual, such as maximal and resting heart rates (Riebe, 2018). This relative (individualised) approach has widely been accepted in terms of scientific rigour but is now growing in popularity in the general population in part due to the accessibility that wearable devices now offer in terms of heart rate measurement and real-time data collection that can be used to gauge intensity, duration and exercise modality (Etkin, 2016; Jang et al., 2018). The wearable devices market is expanding rapidly, with the most popular device, the smartwatch, growing in the last five years. For example, the Apple Watch™ (the most popular smartwatch) now has over 100 million active users (Statista, 2022a). The use of wearable technology for measuring and guiding physical activity has been reported to improve the tailoring of exercise and physical activity to the individual and overall adherence (Coughlin and Stewart, 2016; Hannan et al., 2019).

There are several methods employed to individualise intensity using relative methods. A number of variables recognised by the American College of Sports Medicine (ACSM) have sought to use measures of maximal physiological capacity, including maximal oxygen consumption (VO_{2max}), peak oxygen uptake (VO_{2Peak}), maximal heart rate (HR_{max}) and peak heart rate (HR_{peak}) to prescribe intensity (Riebe, 2018). These measures, usually derived from a maximal graded exercise test, can also be predicted using formulas based on age (Tanaka, Monahan and Seals, 2001; Gellish et al., 2007; Whyte et al., 2008) and extrapolated from submaximal exercise tests (Cink and Thomas, 1981; Liu et al., 2010; Ferrar et al., 2014) with good accuracy (Macsween, 2001; McFadden and Li, 2019). Other relative methods of individualising intensity seek to incorporate both maximal and/or resting values as a means of regulating physical activity and exercise prescription based on fitness/health status, (Serrano et al., 2017; Abt et al., 2019; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019). Resting heart rate is an indicator of cardiorespiratory health, improved quality of life and improved life expectancy (Liu et al., 2010; Jensen et al., 2013). Incorporating resting, alongside maximal values, using percentage heart rate reserve (%HRR) and percentage $VO_{2reserve}$ (%VO_2R), has the potential to improve validity of exercise and physical activity prescription when compared to using maximal data only (Lounana et al., 2007; Pinet et al., 2008). Yet there are some limitations with this method if physical activity is recorded manually, as resting heart rate can be improved with physical activity and lifestyle modification in as little as 6 – 10 weeks (Norris, Carroll and Cochrane, 1992; Cohen et al., 2011; Jang et al., 2018) and several internal and external factors such as age and lifestyle, can alter resting heart rate (Valentini and Parati, 2009). However, wearable devices can now measure heart rate continuously. For example, the Apple Watch™ records resting heart rate values during sedentary periods throughout the day and when sleeping (Apple, n.d.), providing mean daily, weekly, and monthly resting heart rate data. These automated methods of data collection can overcome potential barriers in collating accurate resting measurements required for this method of exercise prescription.

Given that intensity can be measured through both absolute and relative methods, it is important that we understand how these methods relate to each other and that we know the agreement between absolute and relative intensity measures. There is the potential for large disagreement, given that relative methods are based on the individual's cardiorespiratory fitness and/or other individualised measures. The agreement or disagreement between absolute and relative intensity methods has implications for physical activity and exercise prescription and for how physical activity is promoted and measured in the general population, specifically when walking. Therefore, the purpose of this systematic review with meta-regression was to investigate the agreement and relationship between absolute (METs) and relative intensity methods during walking.

4.2 Methods

4.2.1 Protocol and registration

This systematic review with meta-regression was designed and written using the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Page et al., 2021), and pre-registered on the Open Science Framework osf.io/4md3z prior to conducting the first literature search.

4.2.2 Eligibility criteria

Studies were only considered if they met the following inclusion criteria: published in English, peer-reviewed, focused on walking and included both absolute and relative intensity measures. To be eligible for inclusion, each study required a minimum of one of the ACSM (Riebe, 2018) criterion measures of relative intensity, %HRR, $\%VO_2R$, percent of heart rate max ($\%HR_{max}$) or percent of maximal oxygen consumption ($\%VO_{2max}$), together with the measurement of METs. We also included other relative measures including HR_{index}, lactate and ventilatory thresholds. The main population focus was adults aged 18-65 years old, apparently healthy and of any sex. Studies were excluded for the following reasons: participants were aged under 18 or over 65 years, full text was unavailable, the study involved animals, or participants had underlying health issues that may have impacted walking gait.

4.2.3 Search strategy and data extraction

A systematic search of four databases (SPORTDiscus, Medline, Academic Search Premier and CINAHL) was completed from the earliest available date to September 2021 (Figure 4.1). Search terms consisted of activity (walking) and intensity (absolute and relative). First, keyword searches were conducted: (i) step* OR walk* OR strid* OR "physical activity"; (ii) absolute OR "absolute intensity" OR mets OR metabolic equivalent OR actigraph* OR acceleromet*; (iii) relative OR "relative intensity" OR "heart rate" OR "heart rate reserve" OR "vo2 reserve" OR vo2* OR "vo2 uptake" OR HRmax* OR metmax. Second, categories (i) to (iii) were combined using 'AND' and duplicates removed. Manual searching of the reference list of identified articles was also undertaken.

References were imported into Mendeley software (Mendeley desktop, Version 1.19.8, London, UK) for data management. After duplicates were removed, the titles and abstracts were screened independently based on the inclusion criteria by two reviewers (AW and either AB, GA, or NV) using Rayyan online software (Ouzzani et al., 2016). The full text of each potentially eligible study was retrieved and assessed independently by two reviewers (AW and either AB, GA, or NV) using the eligibility criteria. Discrepancies that could not be resolved by discussion were resolved by a third reviewer (AB or GA). Extracted data included: study setting, study population, participant demographics, relative intensity measure, absolute intensity measure and walking protocol. Missing data were requested from authors.

4.2.4 Assessment of methodological quality

Quality assessment was evaluated by two authors (AW, GA), with a third author involved to resolve any disagreements (AB or NV). A modified Downs and Black scale (Downs and Black, 1998) were used to rate quality in non-randomised controlled studies. The Downs and Black scale (Downs and Black, 1998) was altered to incorporate questions relevant to the methodological design of the studies included. The modification of questions was completed by two reviewers and agreed by a third author, in line with other adapted models used (see appendix A) in previously published systematic reviews and meta-analyses (Prince et al., 2008; Warburton et al., 2010). The Downs and Black scale (Downs and Black, 1998) evaluates the quality of reporting, external validity, bias, confounding variables and power. Usually based on 27 criteria, the modified scale used a criterion of 13 items. Quality ratings were also adapted to provide relevant quality outcomes (see appendix A).

4.2.5 Data collection

Raw data were requested from authors of all eligible studies included in this systematic review with meta-regression. Of all authors contacted, six did not respond to our communication, two authors no longer had the data available, and four were unable to supply additional data due to ethical reasons (no detail supplied). Where possible comparable (relative) variables (Dos Anjos et al., 2011; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020) were amalgamated to create one large data set.

Data were extracted from each eligible laboratory trial and stage. i.e., those that had completed a multistage incremental protocol, and provided relative and absolute values of intensity at each incremental stage.

4.2.6 Data analysis

A narrative synthesis of the outcome measures and methodology was first undertaken. Data were also assessed for heterogeneity and a meta-regression conducted using a Bayesian random-effects approach (Kruschke and Liddell, 2018). There are several advantages to this approach over traditional methods: (1) the ability to estimate between-study heterogeneity along with its uncertainty, (2) allocate more weight to the results of particular types of study (e.g., randomised controlled trials), (3) provide exact likelihoods, (4) allow for uncertainty in all parameters, (5) allow for other sources of evidence (e.g., prior distributions), and (6) allow direct probability statements using different measurement scales (Bedding and Lilly, 2004). The approach took the point estimate and standard error from individual studies and modelled these to produce an overall population Cohen's *d* estimate for the effects of interest along with a measure of between-study variability. Data modelling was conducted using R (R Core Team, 2018). The brms package (Bürkner, 2018) was used to perform this modelling, which is a package that uses Stan as the MCMC engine (Bürkner, 2017). Subgroup analysis was conducted considering study design (e.g., experimental; randomised controlled trials, non-randomised controlled trials, intervention, observational and free-living design) as well as physical activity intensity – absolute (METs) and relative (%VO_2R %HRR, %HR_{peak}, %VO_{2max}, HR_{index}, lactate and ventilatory thresholds). A Bayesian regression was conducted to quantify the relationship between METs and %HRR, where a modelling approach was taken by fitting models with different response distributions and selecting and reporting the models with the best out of sample predictive performance using Leave-One-Out Cross Validation (LOO) to compare the expected log-predictive density (ELPD) of models (Vehtari, Gelman and Gabry, 2017). We report population uncertainty as 95% credible intervals.

4.3 Results

4.3.1 Description of studies

A total of 15,918 papers were identified from the preliminary keyword search (see Figure 4.1). Prior to title and abstract screening, 6,144 records were excluded, including 5,547 duplicates and 597 animal studies. After title and abstract screening, 9,774 papers were eliminated based on the exclusion criteria, 6 additional papers were obtained from hand searches leaving 140 records for full-text review. The full-text review excluded 125 papers resulting in a total of 15 studies that met the inclusion criteria, (Spelman et al., 1993; Brooks et al., 2005; Hagins, Moore and Rundle, 2007; Ham et al., 2007; Tumiati et al., 2008; Kilpatrick et al., 2009; Dos Anjos et al., 2011; Sell et al., 2011; Ozemek et al., 2013; Agiovlasitis, Sandroff and Motl, 2016; Nakanishi et al., 2018; Caballero et al., 2019; Gil-Rey et al., 2019a; Sweegers et al., 2020). Common reasons for exclusion were participant age exceeded 65 years; exercise modality was not walking; and a direct comparison between a relative and absolute measure of physical activity was missing. All included studies reported at least one measure of absolute intensity (METs) and one relative measure of intensity (%HRR, $\%VO_2R$, $\%HR_{max}$, $\%VO_{2max}$, HR_{index}, lactate threshold, ventilatory threshold). However, four studies were excluded from the assessment of agreement when based on the reported means (Spelman et al., 1993; Gil-Rey et al., 2014; Bertapelli et al., 2019; Gil-Rey et al., 2019a; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019) because either, the absolute and relative values reported in these studies (Spelman et al., 1993; Gil-Rey et al., 2014; Bertapelli et al., 2019; Gil-Rey et al., 2019a; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019) could not be directly compared using the ACSM intensity classification scheme (Liguori, 2022) or mean and SD data were not reported (Spelman et al., 1993; Gil-Rey et al., 2014; Bertapelli et al., 2019; Gil-Rey et al., 2019a). A further three studies (Dos Anjos et al., 2011; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020) were excluded from the assessment of agreement based on the reported means, either because the data from these studies were used in the comparison of agreement based on raw data (Dos Anjos et al., 2011; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020) or used in the meta-regression (Dos Anjos et al., 2011; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020). This resulted in eight studies being examined for agreement when based on mean values (Spelman et al., 1993; Brooks et al., 2005; Hagins, Moore and Rundle, 2007; Tumiati et al., 2008; Kilpatrick et al., 2009; Sell et al., 2011; Nakanishi et al., 2018; Caballero et al., 2019).

4.3.2 Study quality

Studies were graded on a modified Downs and Black (Downs and Black, 1998) scale, with a mean (SD) rating of 10.2 (1.2) from a maximum of 16, with a range of 7-12 (Table 4.1).

1.3.3 Systematic review

4.3.4 Characteristics of study population

Participant characteristics from the 15 studies included in this review are displayed in Table 4.2. Sample size ranged from 12 – 210 participants, with a mean (SD) sample size of 54 (48) participants. Participant age ranged from 25 – 61 years with a mean (SD) age of 38.8 (11.5) years. Gender was 70% female. Participant geographical location included United States (7 studies), Japan (2 studies), Spain (2 studies), Italy (1 study), Netherlands (1 study) Australia (1 study) and Brazil (1 study).

4.3.5 Agreement between mean absolute and mean relative intensity

Based on eight studies (Spelman et al., 1993; Brooks et al., 2005; Hagins, Moore and Rundle, 2007; Tumiati et al., 2008; Kilpatrick et al., 2009; Sell et al., 2011; Nakanishi et al., 2018; Caballero et al., 2019), a comparison of mean absolute (METs) and mean relative (%HRR, $\%HR_{max}$, $\%VO_2R$, $\%VO_{2max}$, HR_{index}) intensity was conducted. 'Agreement' was operationally defined when both the mean absolute intensity and mean relative intensity values were classified as the same level of intensity using the exercise intensity guide published by the ACSM (Table 4.1 from (Liguori, 2022)) For example, if mean METs was 4 and mean %HRR was 50%, then we classified this as 'agreed', because both values would be classified as 'moderate' intensity according to the guidelines. Whereas, if mean METs was 4 and mean %HRR was 35%, then this was classed as 'not agreed', because METs would be classified as 'moderate' intensity yet %HRR would be classified as 'light' intensity. From eight studies (n=299 participants) there was 60% agreement between mean absolute and relative intensity categories when based on the ACSM guidelines for cardiorespiratory intensity (very light, light, moderate, vigorous or near maximal) (see Table 4.3).

4.3.6 Agreement between raw absolute and raw relative intensity

In addition to the examination of agreement between mean absolute and relative intensity, we also examined the agreement between raw data from individual participants. Raw data were obtained from three authors, from four separate studies (Dos Anjos et al., 2011; Gil-Rey et al., 2019a; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020). Three studies had comparable relative intensity (Dos Anjos et al., 2011; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020) variables and were compiled into one large data set, totalling 290 participants. The fourth study (Gil-Rey et al., 2019) was excluded from this analysis because there is no intensity classification for lactate threshold that enables comparison with the ACSM classification scheme, and therefore METs. A Bayesian random intercept logistic regression was conducted to examine the agreement between relative and absolute intensity (Figure 4.2), showing an agreement between absolute and relative intensity in 43% of all trials from these three studies.

4.3.7 Relationship between absolute and relative intensity

Two studies (Dos Anjos et al., 2011; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019) had identical relative variables (%HRR) and were compiled into a dataset containing 1257 individual data points from 240 participants. A series of Bayesian random intercept regression models were developed to quantify the relationship between METs and %HRR. The best performing model was a log-log regression model (Figure 4.3) which indicated that for every 1% increase in METs, %HRR increased by 1.12% (95% CI: 1.10 – 1.14). Specifically, the model predicts at the lower bound of absolute moderate intensity (3 METs), %HRR is 33% (95%CI: 18 – 57) and at vigorous intensity (6 METs) %HRR is 71% (38 – 100).

Table 4.1 Modified Downs and Black scores for studies included in the systematic review and meta-regression

	Reporting					External validity			Internal Validity				Power	
									Bias			Confounding		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**Total**
Agiovlasitis et al. (2014)	1	1	1	1	1	0	0	1	0	1	1	1	0	9
Tumiati et al. (2008)	1	1	1	1	1	0	1	0	1	1	1	1	0	10
Brooks et al. (2005)	1	1	1	1	1	1	0	1	0	1	1	1	0	10
Caballero et al. (2019)	1	1	1	1	1	1	0	1	0	1	1	1	0	10
Dos Anjos et al. (2011)	1	0	1	1	1	1	0	0	1	0	0	1	0	7
Ham et al. (2007)	1	1	1	1	1	1	0	1	0	1	1	1	0	11
Kilpatrick et al. (2009)	1	1	1	1	1	0	1	0	0	1	1	1	0	9
Nakanishi et al. (2018)	1	1	1	1	1	1	0	1	0	1	1	1	0	9
Ozemek et al. (2013)	1	1	1	1	1	0	1	1	0	1	1	1	0	10
Sell et al. (2011)	1	1	1	1	1	0	1	1	0	1	1	1	0	12
Gil-Rey et al. (2019a)	1	1	1	1	1	0	1	1	0	1	1	1	0	10
Gil-Rey et al. (2019)	1	1	1	1	1	1	0	1	0	1	1	1	0	10
Hagins et al. (2007)	1	1	1	1	1	1	0	1	0	1	1	1	0	10
Spelman et al. (1993)	1	1	1	1	1	0	1	1	0	1	1	1	0	10
Sweeger et al. (2020)	1	1	1	1	1	1	1	1	0	1	1	1	0	11

Table 4.2 Characteristics of the studies included in the systematic review and meta-regression.

Study	Country	Mean (SD) age (years)	N/sex	Absolute measure	Relative measure	HR_{max} measured (direct or equation)	RHR measured (protocol/ direct)	VO_{2max} (measured or estimated)	Measured or standard MET	Walking protocol	Protocol (single stage or multistage)	Walking speed (standardised or self -elected)
Agiovlasitis, Sandroff, & Motl, (2016)	United States	51 (6)	20 F 16 M	METs	HR_{index}	N/A	6 mins seated post 10 mins of sitting	N/A	Measured (seated)	6x 6 min trials overground	Multistage	Standardised
Tumiati et al. (2008)	Italy	Intervention 48 (12) Control 51 (11)	35 F 17 M	METs	%HRR	Equation	Not reported	Not reported	Standard	2km·h^{-1} brisk walk on indoor track	Single stage	Self-selected
Caballero et al. (2019)	Japan	F 38.0 (11.7) M 39.5 (10.6)	20 F 20 M	METs	%HRR	Equation 208 – (0.7xage)	7-minute seated average taken every minute	N/A	Measured (seated 7 minutes)	3 treadmill walking conditions	Multistage	Standardised
Dos Anjos et al. (2011)	Brazil	43.8 (20.2-64.9)	121 F 89 M	METs	%HRR	Equation (Gellish et al., 2007) measured	Measured, using a 40-minute supine protocol	N/A	Measured (seated 10 mins)	6x3 min treadmill stages	Multistage	Standardised
Ham et al. (2007)	USA	31 (4.3)	7 F 5 M	METs	%HRR	Equation Karvonen formula (KARVONEN,, 1957)	Not reported	N/A	3 previously outlined accelerometer cut points	Ambulatory data	N/A	N/A
Kilpatrick et al. (2009)	USA	25.8 (7.9)	9 F 11 M	METs	%HRR $\%VO_2R$	Measured	Predicted	Estimated	standard	Walking performed at 2.5 mph for women 3.0 mph for men. incline increased by 2% every minute until an RPE of 13 was achieved.	Multistage	Standardised
Nakanishi et al. (2018)	Japan	38.65 (11.13)	21 F 21 M	METs	%HRR	Calculated Karvonen formula	Measured 7 minutes seated	N/A	Standard	Overground laboratory trials using a pace leader	Single stage multiple speeds	Standardised
Ozemek et al. (2013)	USA	F 25.7 (5.7) M 28.8 (7.2)	35 F 38 M	METs	%HRR	Measured	Measured (protocol not reported)	Measured (submax 85% HR_{max})	Standard	5-minute incremental treadmill stages	Multistage	Standardised
Sell et al. (2011)	USA	24 (4)	18 F 6 M	METs	$\%VO_2R$	Measured	Measured 15 minute seated	Measured	Measured	30-minute Treadmill	Single stage	Self-selected

Erreka Gil-Rey, et al. (2019)	Spain	Low fit 61.4 (5.8) High fit 56.6 (4)	88 F 0 M	METs	LT	N/A	N/A	N/A	Measured	Incremental shuttle test	Multistage	Standardised
Gil-Rey et al. (2019)	Spain	57.2 (5.0)	30 F 0 M	METs	%HRR %VO_{2max}	Measured	N/A	Measured	Measured	overground walking trials	Multistage	Standardised
Hagins et al. (2007)	USA	31.4 (8.3)	18 F 2 M	METs	%HR_{max}	208 - (0.7 x age)	N/A	N/A	Measured	10-minute treadmill trials	2 stage	Standardised
Brooks et al. (2005)	Australia	F 39.9 (2.8) M 40.0 (3.3)	36 F 36 M	METs (predicted)	%HR_{max}	Predicted (208-0.7x age)	N/A	N/A	Measured	15-minute overground walking	Single	Self-selected
Spelman et al. (1993)	USA	34.9 (8.6)	22 F 7 M	METs	%VO_{2max} %HR_{max}	Measured	No reported	Measured	Measured	8 min treadmill trials	Single stage	Self-selected
Sweegers et al. (2020)	Netherlands	49.9 (9.0)	50 F 0 M	METs	% VO_{2peak}	Measured	Measured in supine position	Measured	Measured	6 minutes treadmill trials	Multistage	Standardised

Table 4.3 Mean (SD) for measures of relative and absolute exercise intensity from each study included in the systematic review and meta-regression.

Author	Speed	Classification	Predicted METs	Measured METs	%HRR	$\%VO_2R$	$\%HR_{max}$	$\%HR_{peak}$	$\%VO_{2max}$	$\%VO_{2peak}$	HR_{index}
Agiovlasitis et al. 2014	0.5 $m \cdot s^{-1}$	*	-	2.23 (0.44)	-	-	-	-	-	-	1.33 (0.11)
	0.75 $m \cdot s^{-1}$	*	-	2.59 (0.48)	-	-	-	-	-	-	1.37 (0.14)
	1 $m \cdot s^{-1}$	*	-	2.96 (0.52)	-	-	-	-	-	-	1.5 (0.14)
	1.25 $m \cdot s^{-1}$	*	-	3.53 (0.59)	-	-	-	-	-	-	1.72 (0.12)
	1.5 $m \cdot s^{-1}$	*	-	4.43 (0.87)	-	-	-	-	-	-	2.06 (0.31)
	Preferred walking speed	*	-	4.07 (1.08)	-	-	-	-	-	-	1.57 (0.24)
Tumiati et al. (2008)	Self-selected pace 2 km WT	1	3.8 (1.0)		55 (14)						
		1	3.7 (1.2)		56 (13)						
		1	4.4 (0.9)		59 (1.1)						
		0	4.8 (1.3)		63 (11)						
		1	3.5 (1.1)		54 (13)						
		1	3.3 (0.6)		55 (13)						
		1	3.4 (1.1)		52 (14)						
		1	3.3)1.3)		50 (19)						
Caballero et al. (2019)	55 $m \cdot min^{-1}$	0	3.3 (0.5)	-	21.8 (5.3)	-	-	-	-	-	-
	70 $m \cdot min^{-1}$	0	3.7(0.5)	-	26.0 (8.0)	-	-	-	-	-	-
	100 $m \cdot min^{-1}$	0	5.1 (0.9)	-	36.5 (10.8)	-	-	-	-	-	-
	13 $m \cdot min^{-1}$	0	9.45 (1.5)	-	73.4 (12.6)	-	-	-	-	-	-
Kilpatrick et al. (2009)	Averages at 13 RPE	0 1 1 1	5.8 (1.5)	-	61.9 (16.9)	46.8 (14.7)	75.6 (10.5)	-	51.5 (1.5)	-	-
Nakanishi et al., (2018)	55 $m \cdot min^{-1}$	0	3.35 (0.54)	-	18.81 (9.1)	-	-	-	-	-	-
	70 $m \cdot min^{-1}$	0	3.75 (0.5)	-	23.37 (9.14)	-	-	-	-	-	-
	100 $m \cdot min^{-1}$	0	5.12 (0.88)	-	34.16 (11.87)	-	-	-	-	-	-
Sell et al. (2011)	Self-selected brisk walk	1	-	4.8 (1.3)	-	41.2 (3.5)	-	-	-	-	-
Hagins et al., (2007)	3.2 $k \cdot mh^{-1}$	0	-	2.5 (0.4)	-	-	50.7 (8.0)	-	-	-	-
	4.8 $k \cdot mh^{-1}$	1	-	3.3 (0.4)	-	-	58.1 (10.7)	-	-	-	-
Brooks et al. (2005)	Men - 5.2 (0.6)	1	3.76 (0.53)		-	-	52 (7)	-	-	-	-
	Women- 5.5 (0.5)	1	4.1 (0.58)	-	-	-	61 (9)	-	-	-	-

Spelman et al. (1993)	Habitual walking speed	1	5.1 (1.2)	-	-	-	-	-	51.5 (1.2)	-	-
Dos Anjos et al. (2011)	1.11 $m{\cdot}s^{-1}$ 0%	**	3.1 (0.03)	3.8 (0.1)	40.7 (1.3)	-	-	-	-	-	-
	1.56 $m{\cdot}s^{-1}$ 0%	**	4.0 (0.04)	5.0 (0.1)	56.0 (1.5)	-	-	-	-	-	-
	1.56 $m{\cdot}s^{-1}$ 2.5%	**	4.7 (0.04)	5.8 (0.1)	66.0 (1.9)	-	-	-	-	-	-
	1.56$m{\cdot}s^{-1}$ 5%	**	5.3 (0.05)	6.5 (0.1)	72.3 (1.9)	-	-	-	-	-	-
	1.56 $m{\cdot}s^{-1}$ 7.5%	**	6.1 (0.06)	7.3 (0.1)	77.5 (1.6)	-	-	-	-	-	-
	1.56 $m{\cdot}s^{-1}$ 10%	**	6.9 (0.07)	8.2 (0.1)	81.7 (2.2)	-	-	-	-	-	-
Sweegers et al. (2020)	3.2 $k{\cdot}mh^{-1}$ 0%	**	3.5 (0.9)	-	-	-	-	-	51.0 (17.7)	-	-
	4.8 $k{\cdot}mh^{-1}$ 0%	**	4.4 (0.9)	-	-	-	-	-	60.8 (16.0)	-	-
	5.5 $k{\cdot}mh^{-1}$ 5%	**	6.3 (1.3)	-	-	-	-	-	83.8 (15.0)	-	-
Gil-Rey et al. (2019)	-	$	-	-	-	-	-	-	-	-	-
Gil-Rey et al. (2019)	-	$	-	-	-	-	-	-	-	-	-
Ham et al. (2007)	-	$	-	-	-	-	-	-	-	-	-
Ozemek et al. (2013)	-	$	-	-	-	-	-	-	-	-	-

1 There is agreement between absolute and relative intensity
0 There is no agreement between absolute and relative intensity
*The absolute and relative values for this study cannot be compared because there is no guidance on how HR_{index} can be classified into light, moderate and vigorous intensity thresholds.
** The absolute and relative values for this study cannot be compared as the raw values are compared in figure 2.
$ The absolute and relative values for this study cannot be compared as the authors have not provided mean (SD) data for the walking trials

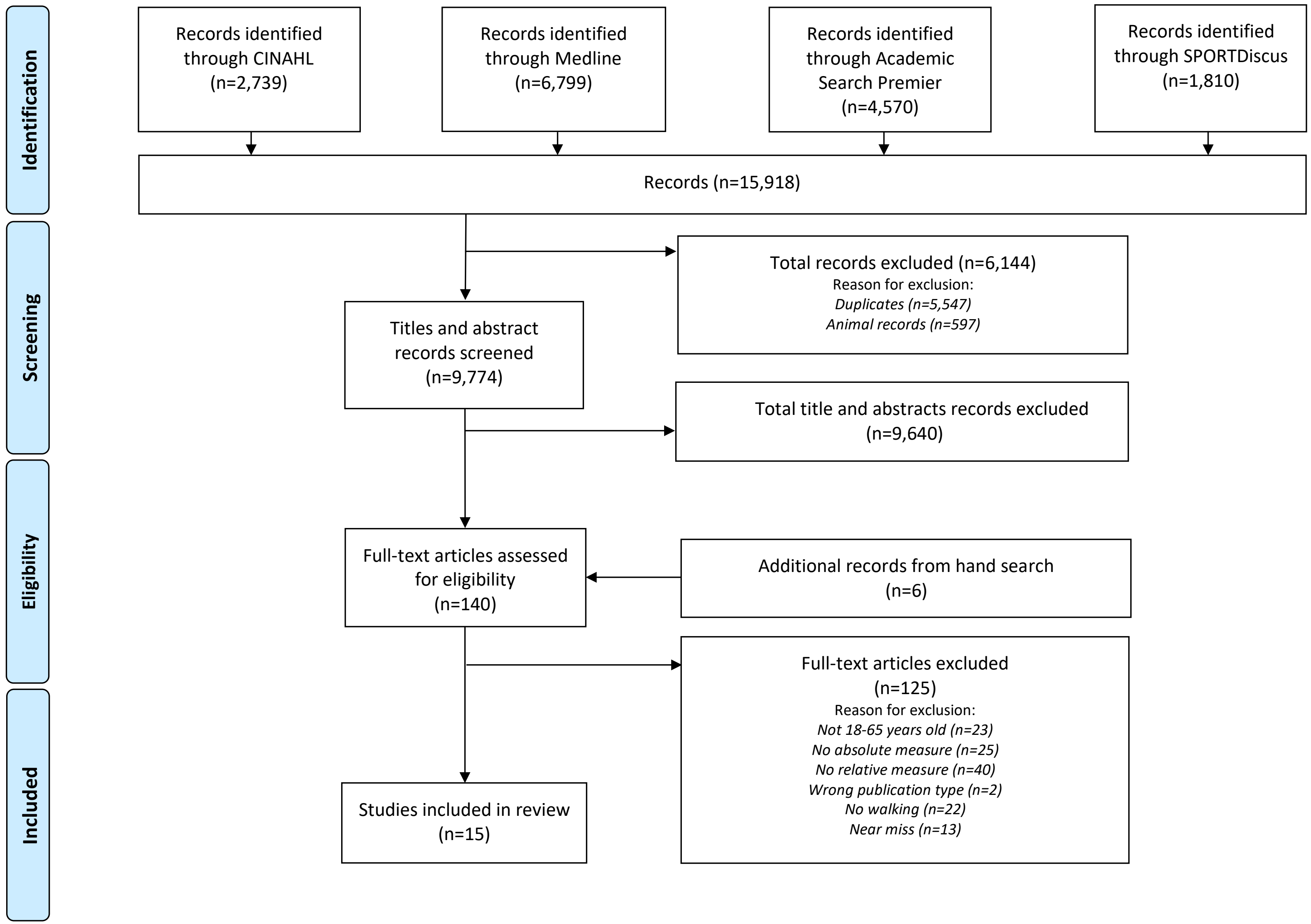

Figure 4.1 PRISMA flowchart

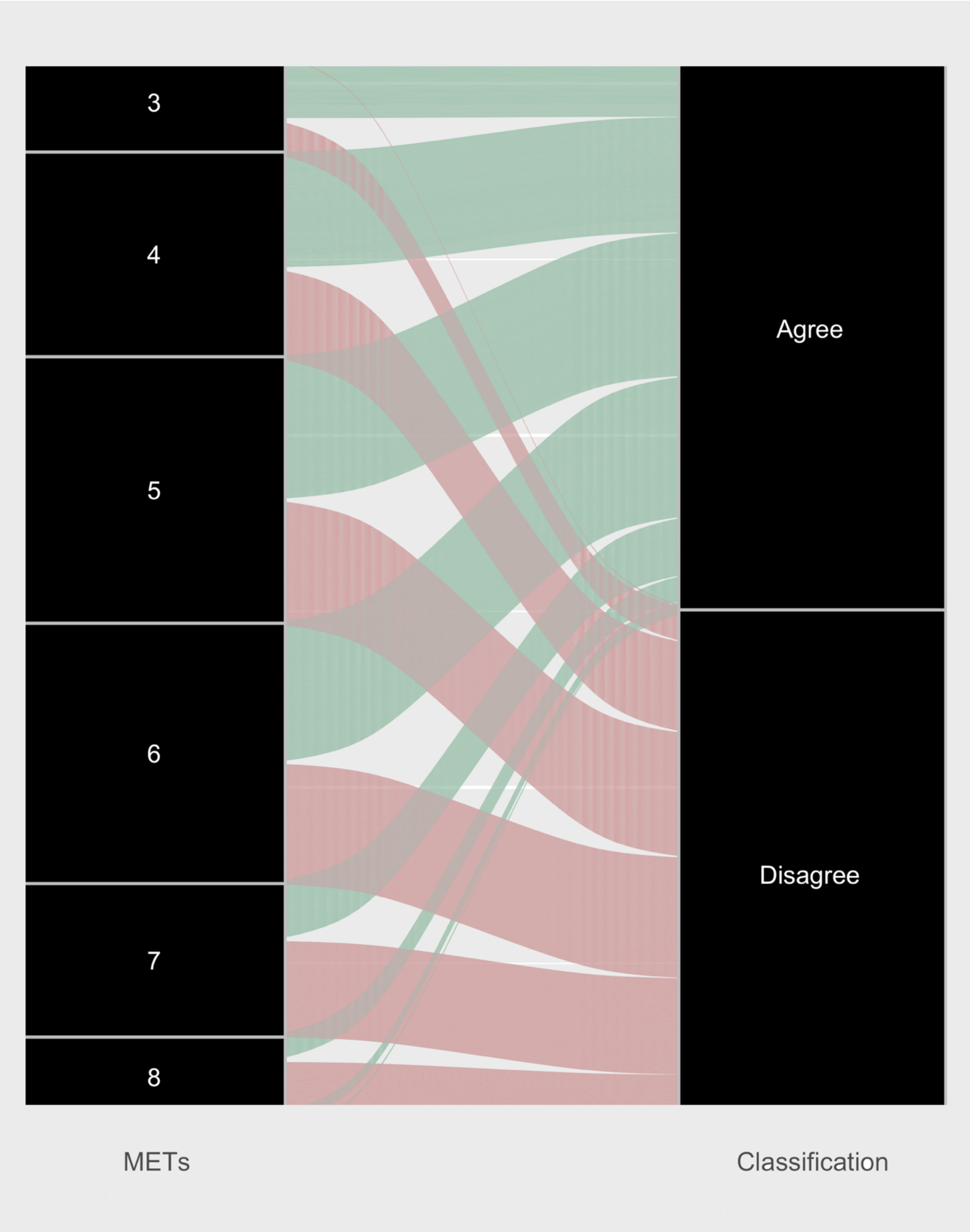

Figure 4.2 The agreement between absolute and relative measures of moderate-to-vigorous exercise intensity when based on raw data from three studies (Dos Anjos et al., 2011; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020).

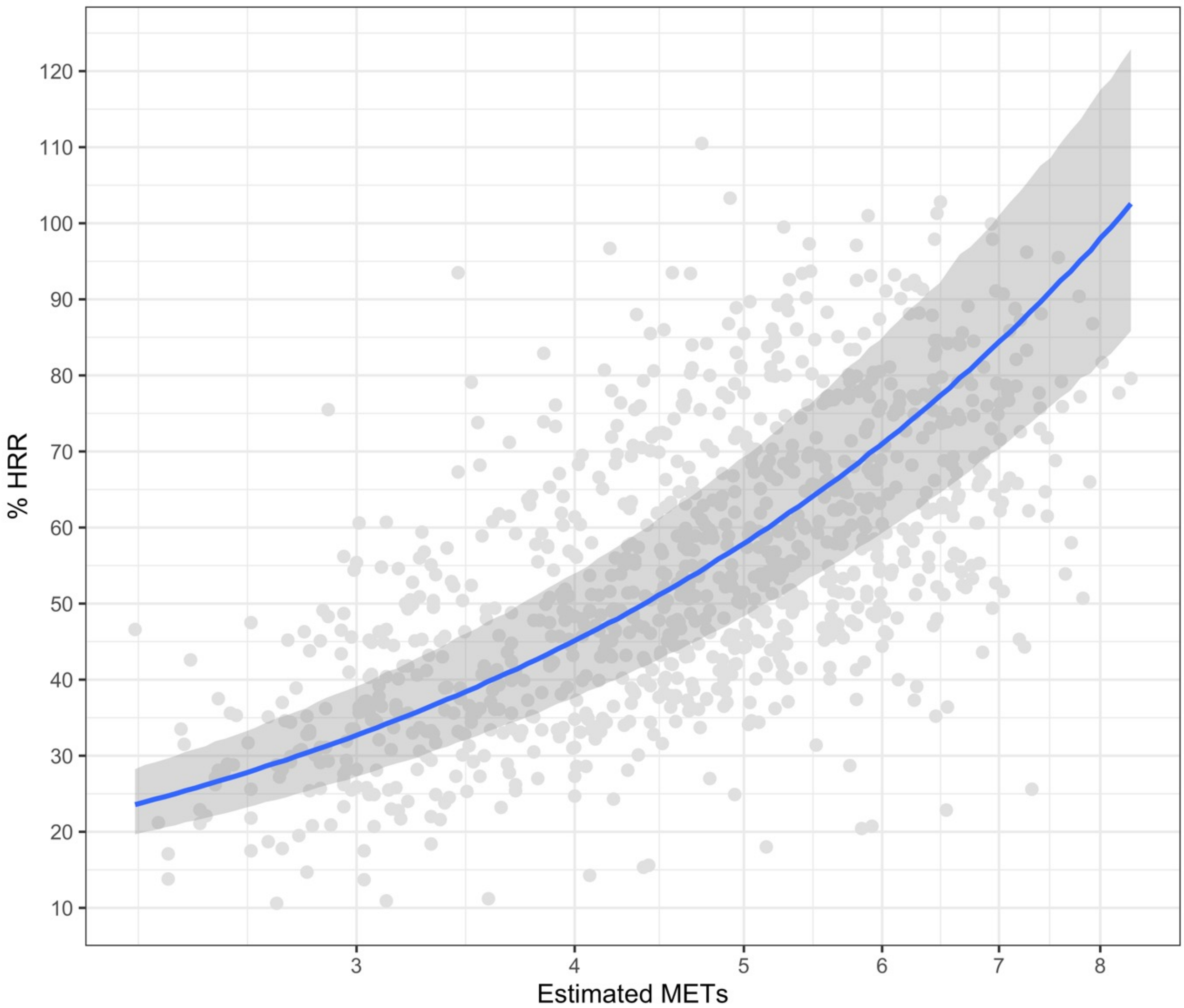

Figure 4.3 The number of data points =1257 due to each participant contributing multiple data points from multistage incremental tests. Please note that 5 data points for %HRR are above 100%, which is physiologically implausible. However, these are the data we obtained from the authors.

There was no deviation from the pre-registration.

4.4 Discussion

The aim of this systematic review with meta-regression was to examine the agreement and relationship between absolute and relative intensity when measured during walking. The main findings are: (1) a large disagreement exists between absolute and relative intensity across the intensity spectrum; (2) the relationship between absolute and relative intensity suggests that METs overestimates moderate intensity; and (3) a large inter-individual variation exists in relative intensity for any given value of absolute intensity.

4.4 Systematic review

4.4.1 Study characteristics

All 15 studies used METs as their absolute measure of intensity. However, several measures were used for relative intensity. The most common relative method was %HRR (8 studies) [57,69–74,79], followed by %HR_{max} (3 studies) (Spelman et al., 1993; Brooks et al., 2005; Hagins, Moore and Rundle, 2007), %VO_{2max} / %VO_{2peak} (3 studies) (Kilpatrick et al., 2009; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019; Sweegers et al., 2020) %VO_2R (2 studies) (Kilpatrick et al., 2009; Sell et al., 2011), lactate thresholds (2 studies) (Gil-Rey et al., 2019a; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019), and HR_{index} (1 study) (Agiovlasitis, Sandroff and Motl, 2016) . This large variation in relative intensity methods may indicate why METs have become a popular choice among research and industry professionals as their use has been standardised as a measure of intensity.

4.4.2 Study quality

The quality score for included studies is reported in Table 4.1. Eleven of fifteen studies included in this review scored 10 or above highlighting that, in general, the quality of studies was acceptable. Question thirteen relates to the completion and reporting of power calculations. For a study to obtain four points for this criterion, *a priori* power calculation was required, with associated inputs reported and the correct number of participants recruited. All studies included in this review failed to meet any of this criterion, with none reporting a sufficiently completed *a priori* power calculation. This further highlights the need for reporting guidelines, such as STROBE, when designing and reporting observational studies. Adhering to guidelines and sufficiently powering studies is a key component of robust methodological design, and one that may significantly impact the validity and reliability of findings (Schäfer and Schwarz, 2019). Question nine highlighted the need for pre-registration of studies prior to data collection and subsequent publication. Only two of the included studies pre-registered their methods and expected outcomes (Tumiati et al., 2008; Dos Anjos et al., 2011). There are a number of benefits of improving transparency of academic publishing, through the process of pre-registration, not least the reduction of bias and exaggeration of findings and may also suppress or prevent p-hacking, HARKing and cherry picking (Yamada, 2018) as hypotheses and analytical methods are declared prior to experimental trials being performed. Reducing the risk of bias within study design is fundamental to scientific rigour, and it is strongly recommended that future studies include sample size estimation and pre-registration to reduce risk of bias and improve the transparency of scientific publication.

4.4.3 METs

There are discrepancies in how METs are measured, and three approaches were used in the included studies. In its most absolute form, an arbitrary resting MET of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ was used to prescribe and record intensities. This value was then multiplied to describe the intensity, which is a method that is traditionally used by accelerometers to develop velocity cut points (Spelman et al., 1993; Brooks et al., 2005; Hagins, Moore and Rundle, 2007; Ozemek et al., 2013; Gil-Rey et al., 2019a; Sweegers et al., 2020). That is, 3 METs (moderate intensity), should correspond to a VO_2 of approximately 10.5 $mL \cdot kg^{-1} \cdot min^{-1}$. However, there is evidence to suggest this standardised resting VO_2 value is not accurate for large portions of the population (Byrne et al., 2005; O'Brien et al., 2018), and could therefore contribute to overestimating moderate intensity. Five of the 15 studies in this review used this method for calculating METs (Tumiati et al., 2008; Kilpatrick et al., 2009; Nakanishi et al., 2018; Caballero et al., 2019; Gil-Rey et al., 2019a; Sweegers et al., 2020).

METs can also be measured via breath-by-breath gas analysis, whereby measured VO_2 is divided by 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ to provide a MET intensity (measured METs). Two studies used this method (Spelman et al., 1993; Brooks et al., 2005). A separate hybrid method of determining METs used in four studies (Hagins, Moore and Rundle, 2007; Sell et al., 2011; Agiovlasitis, Sandroff and Motl, 2016; Sweegers et al., 2020) incorporates resting VO_2 sampled from breath-by-breath gas analysis as its 1 MET value. Variation in the measured resting VO_2 will also arise from different methods employed to obtain resting VO_2, as there is no criterion method (Hagins, Moore and Rundle, 2007; Sell et al., 2011; Agiovlasitis, Sandroff and Motl, 2016; Sweegers et al., 2020). This resting MET value is then divided into the breath-by-breath VO_2 to provide a more individualised intensity categorisation.

4.4.4 Agreement between absolute and relative intensity methods

When examining the agreement between absolute and relative intensity, there were large disagreements between the two methods. When mean absolute and mean relative measures were compared in 8 of the 15 studies, there was 60% agreement. This indicated that a large proportion of absolute physical activity (METs) were classified differently when compared to relative measures. The disagreement between absolute and relative intensity was also highlighted in the larger raw data set, from data provided by three authors (Dos Anjos et al., 2011; Gil-Rey et al., 2019; Sweegers et al., 2020). In this case, there was only a 43% agreement between absolute (METs) and relative measures (%HRR, %VO_2peak) (Figure 4.2). This clear disagreement between absolute and relative methods indicates large discrepancies when measuring intensity at an individual level. Clearly, an absolute measure of intensity such as METs is participant independent. That is, the physiological capacity of individuals will not be captured by an absolute measure such as METs. Even in the studies using measured METs, and measured resting VO_2, the ability of a MET to capture the physiological response in an individual relative to their cardiorespiratory fitness is limited. The classification of intensity categories observed in our review has implications for both research and practice. For example, if moderate, vigorous physical activity (MVPA) is overestimated in individuals who are monitoring their physical activity based on METs, then the return on their physical activity investment will be lower than expected.

4.4.5 Relationship between raw absolute and raw relative intensity

The results of the Bayesian random intercept regression based on 240 participants and 1257 data points highlight that at 3 METs (absolute moderate intensity) the equivalent relative intensity is approximately 32%, substantially under the criterion 40% HRR required to meet moderate intensity reported in the ACSM guidelines (Liguori, 2022). However, the 95% credible interval of 18% to 57% emphasises the wide spread of relative intensity observed at 3 METs. This large variation in relative intensity at 3 METs implies that individuals could be performing relative physical activity spanning from very light intensity to the upper bound of moderate intensity when exercising at an absolute moderate intensity of 3 METs. At the lower bound of moderate intensity, the minimum intensity recommended for optimal health outcomes (Bull et al., 2020; nhs.uk, n.d.), this sample were substantially under (10%) the required 40% minimum relative value. These findings suggest large inaccuracies in using absolute measures of physical activity intensity and provides further evidence that an individualised approach to physical activity intensity using relative measures should be considered.

From the Bayesian random intercept regression, it was only at 8 METs that all individuals' relative intensity was classified as moderate, reinforcing the large discrepancy associated with absolute measures of physical activity intensity. Using METs to prescribe and monitor exercise and physical activity has clear limitations within its measurement properties and has the potential to be misguiding for a large proportion of the population (Byrne et al., 2005; Kozey et al., 2010). These results have important health implications. The validity of moderate intensity measurement, in addition to the large level of disagreement between intensity classifications, indicates the possibility of overestimation of total daily and weekly physical activity performed when using absolute measures.

The results of this systematic review with meta-regression indicate that measures of absolute and relative intensity often disagree, and therefore relative intensity should be more highly prioritised in physical activity guidelines and in health promotion messaging. In the past, absolute intensity was preferred probably because the technology for measuring relative intensity was either not available or inappropriate. However, the expanding use of wearable devices by the wider population and the seismic growth in the wearable market (Electronics et al., 2021) now offer the ability to use relative measures of intensity more easily. Evidence suggests that heart rate measured at rest and during walking by photoplethysmography sensors embedded in wearable devices is very accurate (Khushhal et al., 2017; Dunn et al., 2021; Pipek et al., 2021). Individualised physical activity relative to cardiorespiratory fitness is now more readily available, due to wearable devices, and therefore, physical activity monitoring and prescription should adopt relative intensity measures as part of population-based guidelines. We also need more research on the use of relative intensity measures for long-term adherence and effectiveness of physical activity programmes.

4.5 Conclusion

The conclusions drawn from this systematic review with meta-regression highlight the preferential use of METs as a method for quantifying absolute intensity in physical activity studies. However, we present strong evidence to suggest that the validity of METs on an inter-individual basis is not adequate for physical activity prescription and monitoring to maximise potential health benefits. As such, measurement of relative intensity should be more highly prioritised as part of physical activity programmes and guidelines and incorporated into wearable devices, to allow the wider population access to relative individualised intensity thresholds.

5. A comparison between a newly developed Apple Watch app (MVPA) and the Apple Watch 'Exercise' ring for measuring criterion moderate intensity.

5.1 Introduction

There is a substantial body of evidence demonstrating that physical activity reduces morbidity and mortality risk (Barengo et al., 2004; 2017; Nocon et al., 2008; Freitas et al., 2018; Paluch et al., 2022). This has led government organisations like the UK National Health Services (NHS) to advise the public on methods for engaging in physical activity (nhs.uk, 2022). In its guidance, the NHS suggests that engaging in 'moderate' intensity (or above) physical activity leads to health benefits and advises people on how they can gauge 'moderate' intensity using subjective measures. The NHS suggests that moderate intensity,

"…will raise your heart rate, and make you breathe faster and feel warmer. One way to tell if you're working at a moderate intensity level is if you can still talk, but not sing."

(nhs.uk, 2022)

Given these public claims, it is important that they are examined for accuracy via scientific investigation.

As an alternative to these subjective methods of gauging 'moderate' intensity, the ACSM's guidelines for exercise testing and prescription (Liguori, 2022) highlights a number of different methods for measuring exercise intensity, including both relative (%HRR, %HRmax, %VO_{2max}, %VO_2R) and absolute (METs) measures. Relative intensity is described as the exercise intensity relative to the user's physiological capacity (Siddique et al., 2020) and absolute intensity as the energy required to perform an activity (Siddique et al., 2020). However, there is a large disparity between relative and absolute measures of physical activity intensity (Gil-Rey et al., 2019a). For example, (Chapter 4) conducted a Bayesian random intercept logistic regression to examine the agreement between relative and absolute intensity, showing agreement in only 43% of trials. Moreover, a large variation in %HRR at a given MET was reported. Although some researchers in the field suggest that a walking cadence ≥ 100 steps·min^{-1} is an appropriate heuristic value that will allow most people to reach absolute moderate intensity (3 METs) (Tudor-Locke *et al*., 2018, Marshall *et al*., 2009, Nielsen *et al*., 2011, Abel *et al*., 2011), recent evidence suggests this 'one-size-fits-all' approach may be misguided (Serrano et al., 2017; O'Brien et al., 2018; Abt et al., 2019). Recent research using relative intensity (%VO_2R) has highlighted the impact both cardiorespiratory fitness and health status have on the cadence required to reach moderate and vigorous intensity (Abt et al., 2019). Cardiorespiratory fitness plays an integral role in the required walking cadence to reach moderate intensity, which suggests that an individualised prescription of exercise intensity that accounts for the physiological capacity of the individual would be a more appropriate measure of physical activity intensity compared to an absolute measure like METs.

As relative measures of physical activity use percentage thresholds of physiological parameters, they are likely to be more individualised and thus more accurate on an inter-individual basis compared to METs (chapter 4) . However, the main limitation of relative measures and prescription of individualised physical activity has been one of accessibility, or lack of, in a real-world setting. Relative intensity measures routinely collected in laboratory settings, such as oxygen consumption or ventilatory threshold, are currently not feasible outside of a laboratory, mostly due to the inability of wearable devices to collect these measures (Lehtonen et al., 2022). However, the measurement of heart rate, and more specifically heart rate reserve, is now possible using a wearable device. The main advantage of using heart rate reserve is that it is highly associated with oxygen consumption reserve, which is a criterion measure of exercise intensity. Although heart rate devices have been available to the mass market since the 1970's (Kite-Powell, 2022), wearing an ECG chest strap during day-to-day living can be uncomfortable, and thus monitoring physical activity throughout the day using this equipment has not been feasible. However, with the ever-developing wearables market (Global data., 2020), the measurement of heart rate is rapidly becoming mainstream in the 'self-quantification' of physical activity with most modern wearable devices having the capacity to measure heart rate. Recent developments in wearable technology have allowed photoplethysmography (PPG) sensors to measure heart rate data, granting ready access to unobtrusive heart rate measurement throughout the day and night. There are, however, some limitations that have been reported with using a wearable device to measure physical activity, with previous research indicating that wearable devices may not be compatible with current physical activity recommendations, which could be causing people to erroneously perceive that they are exceeding recommendations (Thompson et al., 2016). Yet this effect is usually due to the accelerometer used in wearable devices being an external measure of absolute physical activity intensity, and therefore not individualised to the user. Moreover, Abt et al. (2019) reported that the exercise intensity at which the Apple Watch 'exercise ring' measured that the user was 'exercising' was ~30% VO_2R, suggesting that this device was not accurate at measuring relative intensity and/or guiding the user to exercising at criterion moderate intensity (40% VO_2R). The underestimation of moderate relative intensity would lead to an overestimation of MVPA throughout the day. This is important, because Apple suggest that meeting the default 30 minutes of ‘exercise’ per day (as measured by the Apple Watch) is associated with significant health benefits (Apple, UK, 2023).

So, although the measurement of heart rate via a wearable device now offers a viable option for measuring exercise intensity for millions of people (*Global connected wearable devices 2016-2022*), it would be preferable to use a relative measure of intensity such as heart rate reserve to do so. Heart rate reserve has been reported to be comparable to VO_2R (Swain and Leutholtz., 1997), and therefore offers an accurate, yet feasible method for measuring relative intensity at a population level. As the development of wearable devices grows, it’s important for researchers, exercise professionals, and consumers to understand how relative, individualised measures of MVPA can be used in everyday exercise monitoring, prescription, and goal setting.

Therefore, the main aim of this study was to build on the results of Abt et al. (2019) to examine whether a relative measure of exercise intensity, %HRR, can more accurately measure criterion exercise intensity compared to the native Apple Watch activity app using a larger sample. Secondary aims were (1) to examine the responses to a range of subjective measures that have previously been suggested to reflect ‘moderate’ intensity, and how well those measures predict objectively measured moderate intensity, (2) to examine the differences between methods of determining resting heart, (3) to examine the differences between methods of determining maximal heart rate, and (4) to describe the relationship between walking cadence and %HRR.

5.2 Methods

5.2.1 Study Pre-Registration

The study design, including a statistical analysis plan, was pre-registered prior to data collection, and can be found at https://osf.io/j39fa. STROBE guidelines were adhered to throughout the reporting of this observational study in line with guidelines (von Elm et al., 2007). A STROBE checklist can be found in the appendices (Appendix B).

5.2.2 Ethics

Institutional ethical approval was obtained from the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull (REF – FHS230) additional ethical considerations can be found in the general methods, Chapter 3.

5.2.3 Study Design

This was an observational study, with participants attending the laboratory on two separate occasions. The first visit included medical screening, obtaining written informed consent, resting measures, and measurement of maximal oxygen consumption and heart rate. The second visit was the main experimental trial.

5.2.4 Participants

Participants were aged between 18 and 65 years of age (see Table 5.1. for demographic data) provided written informed consent to participate in the study. Participants were excluded from participation if; 1) they were classified as moderate or high-risk according to the ACSM risk classification criteria (Riebe, 2018), 2) unable to walk on a motorised treadmill, 3) had a BMI ≥ 40), 4) were currently prescribed medication that altered the heart rate response to exercise (e.g., beta-blockers), and 5) had an injury or disability that altered their gait. Participants were recruited from the university and local community through written promotional material and personal communication.

5.2.5 Sample size

As outlined in the study pre-registration, a minimum sample size of 50 participants was required, but with final sample size determined by Bayesian sequential testing until a particular level of precision was attained or, if not achieved, by a stopping rule of 12 months from the beginning of data collection. Bayesian statistical methods are particularly suited to sequential estimation where data comes in a sample at a time and the posterior distribution is updated at each time point (Marsman and Wagenmakers, 2017). The precision required to stop data collection was when the width of the 95% HDI ≤, standard deviation*0.6. Using this criterion, a total of 74 participants completed all trials.

5.2.6 Development of the Apple Watch 'MVPA' app

The app design and technical specification can be found in the general methods section, chapter 3.

5.2.7 Setting

Participants were recruited from May 2021 for a 12-month period. All laboratory trials were completed on campus at the University of Hull.

5.2.8 Preliminary Measures

On entry to the laboratory participants' nude body mass was measured to the nearest 0.1 kg using digital scales (WB-100MA Mark 3, Tanita Corporation, Tokyo, Japan). A wall-mounted stadiometer (Holtain Ltd, Dyfed, Wales, UK) was used to measure stretch stature (Norton *et al.,* 2000).

5.2.9 Resting Oxygen Consumption and Heart Rate

Criterion resting VO_2 and heart rate were measured in a temperature-controlled laboratory. Participants lay in a supine position for 30 minutes with a cushion placed under their head. All other laboratory activity ceased, lights turned off, with participants instructed to relax but not to go to sleep (closing of eyes was permitted). Breath-by-breath oxygen consumption (Cortex Metalyser 3B, GmbH, Germany), and heart rate were recorded continuously. Prior to the commencement of testing, the Cortex Metalyser was calibrated using a 3-point calibration; room air, a known gas concentration of oxygen and carbon dioxide and volume calibrated using a three-litre syringe.

The initial five minutes and final five minutes of oxygen consumption and heart rate data were discarded to allow for habituation, and expectation effects, respectively. The remaining 20 minutes of oxygen consumption and heart rate data were used for the analysis of resting oxygen consumption and heart rate. During minutes 15-20 the MVPA app recorded a resting heart rate value using its built in RHR protocol.

5.2.10 Apple Watch Resting Heart Rate

The 7-day resting heart rate information can be found in the general methods Chapter 3.

5.2.11 Maximal Oxygen Consumption

A graded exercise test completed on a motorised treadmill (h/p/cosmos, Pulsar, Nussdorf-Traunstein, Germany) using a step protocol commencing at 3 $km \cdot h^{-1}$ and a 1% gradient was used to measure maximal oxygen consumption. Treadmill speed was increased by 0.5 $km \cdot h^{-1}$ every 30 seconds until running economy degraded to a point that the participants posture, and technique were affected, incline was then increased every 30 seconds by 0.5% until volitional exhaustion. Oxygen consumption was measured continuously using the same system described in the resting oxygen protocol. Maximal oxygen consumption criteria were 1) a plateau in VO_2 despite an increase in workload, 2) an RER of 1.05, 3) a minimum RPE of 9 (Edvardsen, Hem and Anderssen, 2014).

5.2.12 Experimental trial

Prior to completion of the main exercise trial, participants were instructed to avoid vigorous exercise for 24 hours, maintain their normal diet, and avoid caffeinated drinks for 12 hours prior to trial commencement. The main trial involved participants completing five-minute exercise bouts on a motorised treadmill starting at a walking speed of 3.5 $km \cdot h^{-1}$ and a gradient of 1%. Each subsequent bout increased speed by 0.5 $km \cdot h^{-1}$ until three-minutes of the five-minute bout was recorded as ≥ 40% HRR by the MVPA app and the Apple Watch activity app had recorded five-minutes of 'exercise'. During each five-minute exercise period, participants were told to maintain their normal walking gait, and were not permitted to hold onto the handrails. Oxygen consumption (Cortex Metalysers 3B, GmbH, Germany), and heart rate via ECG chest strap (Polar T31, Polar Electro, OY, Finland) were recorded. Between each walking bout participants had five-minutes of seated rest. Once the treadmill bout had terminated and the treadmill belt was stationary, a chair was placed on the treadmill and participants instructed to sit, motionless, with their hands placed on the treadmill handrail in order to ensure no movement contributed to the measurement of 'exercise' on the native Apple Watch activity app. Five minutes of seated rest was provided to ensure the native Apple Watch activity app had adequate time to update the exercise ring in line with previously reported methods (Abt *et al.,* 2018).

5.2.13 Subjective Measures

During each five-minute bout of exercise, participants were asked a range of subjective measures corresponding to the following NHS guidelines for moderate intensity: '*Moderate activity will raise your heart rate, and make you breathe faster and feel warmer. One way to tell if you're working at a moderate intensity level is if you can still talk but not sing.'*

In the third minute of each stage participants were asked to provide their RPE (category ratio scale 0 – 10) (Borg, 1998), thermal sensation, modified breathlessness (see appendix C) (Borg, 1982), and asked to complete a talk test (Shafer et al., 2000). Following the talk test, participants were asked '*Could you perform the talk test with ease?'*, with participants instructed to answer yes or no. Participants' ratings of thermal sensation, breathlessness, and RPE were compared to objectively measured moderate intensity (40-59% HRR) as measured by the Apple Watch MVPA app. A score of 3 for breathlessness, 8 for thermal sensation, and 3 for RPE were considered as being equivalent to objectively measured moderate intensity if the corresponding %HRR was between 40-59%. The values chosen for each scale were done so if there was a corresponding 'moderate' value on the scale (i.e., for breathlessness and RPE), or in the case of thermal sensation, where the rating was closely aligned with the NHS wording. That is, the NHS suggests that moderate intensity physical activity will make one 'feel warmer', which aligns most closely with a rating of 8 on the thermal sensation scale ('slightly warm').

5.3 Statistical analysis

5.3.1 Statistical models

5.3.2 Walking trials

Data from the native Apple Watch 'Activity' app were compared to data from the novel 'MVPA' app, and to the criterion measure of intensity, %VO_2R. Data from the stage at which at least three-minutes of the five-minute bout met the moderate intensity criterion (40-59% HRR) measured by the 'MVPA' app were compared to data from the stage where all five-minutes of the five-minute bout had been classified as 'exercise' by the native Apple Watch 'Activity' app. %VO_2R and %HRR were analysed separately and different groups of models for these two dependent variables were produced. Posterior distributions were estimated for both the MVPA app, and the native Apple Watch Activity app and these distributions were compared to a 40% VO_2R criterion value measured via ECG chest strap, as well as to each other. In the comparisons between apps and 40% HRR criterion, a Region of Practical Equivalence (ROPE) was used. This ROPE meant that, for practical purposes, values from 37% to 43% were considered equivalent to 40% HRR. The upper and lower boundaries of the ROPE were set from the findings of a previous study completed by this research group (Abt et al., 2019). Posterior distributions of the % HRR, estimated by the MVPA app, the

%HRR at all 5-minutes of the 5-minute bout had been classified as 'exercise' by the native Apple Watch 'Activity' app, and the ECG chest strap were modelled using a series of Bayesian regression models (see models fitted subsection below for further details). In all %HRR estimates, the 40% HRR measured by the ECG chest strap will be considered the response variable.

For %VO_2R, posterior distributions were estimated for both the ‘MVPA’ app, and the native Apple Watch ‘Activity’ app and these distributions were compared to a 40% VO_2R criterion value, as well as to each other. In the comparisons between apps and metabolic cart, a ROPE was used. As with % HRR, the ROPE was set from 37% to 43%. The posterior distributions for the apps and metabolic cart were modelled using a series of Bayesian regression models (see models fitted subsection below) and then compared to determine the best model in terms of out-of-sample prediction accuracy and data fit (see comparison methods subsection below). In all %VO_2R estimates, the %VO_2R measured by the metabolic cart was considered the response variable.

5.3.3 Resting and Maximal Heart Rate protocol

Posterior distributions were produced for all three methods of estimating RHR using the 5-minute protocol on the MVPA app and 7 – day mean resting heart rate protocol; comparisons were made to the posterior distributions of measured RHR using an ECG chest strap. Maximal HR determined how well the bespoke ‘MVPA’ app estimated maximal HR (HRmax), with comparisons made between the bespoke app’s estimated and actual measured HRmax taken during the VO_2max test. To achieve this, posterior distributions were produced for both the measurements. As with the previous analyses, a series of Bayesian regression models were used to obtain the posterior distributions (see models fitted subsection below) and then compared to determine the best model in terms of out-of-sample prediction accuracy and data fit (see comparison methods subsection below).

5.3.4 Subjective Measures

To determine how well participants' ratings of thermal sensation, RPE, and breathlessness predict 'moderate' intensity physical activity, different Bayesian regression models were fitted as follows:

1) To determine how well a Rating of Perceived Exertion (RPE) predicts moderate-intensity physical activity measured using $\%VO_2R$, a posterior distribution of the relationship between $\%VO_2R$ (the response variable) and RPE was estimated using a Bayesian regression model, as well as models fitted with the other response distributions (thermal sensation, talk test, and breathlessness) detailed in the 'Models fitted' section. These models were compared using the methods outlined in the Comparison methods section.

2) To determine how well ratings of thermal sensation predict MVPA ($\%VO_2R$), a posterior distribution of the relationship between $\%VO_2R$ (the response variable) and ratings of thermal sensation was estimated using a Bayesian regression model, as well as models using the other response distributions detailed in the 'Models fitted' section. Again, these models will be compared using the methods outlined in the 'Comparison methods' section.

3) To determine how well ratings from the talk test predicted moderate-intensity physical activity measured using $\%VO_2R$, a posterior distribution of the relationship between $\%VO_2R$ (the response variable) and talk test were estimated using a Bayesian regression model, as well as models fitted with the other response distributions detailed in the 'Models fitted' section. As with the other analyses conducted, these models were compared using the methods outlined in the 'Comparison methods' section.

5.3.4 Models fitted

The models estimating MVPA (40% HRR and 40% VO_2R) were fitted with different response distributions (Gaussian, Skew Normal, and Student's t-distribution) and different prior distributions: 1) general weakly informative prior, 2) a measurement constrained prior that distributes probability over possible values constrained by the measurement, and 3) strongly informative priors, informed by previous studies. Each of these models included: 1) fixed effect models, 2) random intercept models, where intercepts for each individual measure were allowed to vary, and 3) models where both intercepts and slopes for everyone were allowed to vary. This provided a pool of models for each analysis which were compared (see comparison methods subsection below). The basic structure of the fixed effects, random intercept and random slope models are detailed below. These were adjusted to accommodate the different response distributions and priors outlined above. Fixed effects model $\mathrm{yi} \sim \mathrm{Normal}(\mu\mathrm{i}, \sigma\mathrm{e})\ \mu\mathrm{i} = \alpha + \beta\mathrm{xi}$, Random intercept model: $\mathrm{yi} \sim \mathrm{Normal}(\mu\mathrm{i}, \sigma\mathrm{e})\ \mu\mathrm{i} = \alpha\mathrm{j[i]} + \beta\mathrm{xi}\ \alpha\mathrm{j} \sim \mathrm{Normal}(\alpha, \sigma\alpha)$; Random intercept and slope model $\mathrm{yi} \sim \mathrm{Normal}(\mu\mathrm{i}, \sigma\mathrm{e})\ \mu\mathrm{i} = \alpha\mathrm{j[i]} + \beta\mathrm{j[i]xi}\ \alpha\mathrm{j} \sim \mathrm{Normal}(\alpha, \sigma\alpha)\ \beta\mathrm{j} \sim \mathrm{Normal}(\beta, \sigma\beta)$. In these models $\alpha\mathrm{j[i]}$ indicates that each participant is given a unique intercept, issued from a Normal/Gaussian distribution, centred on α, the grand intercept, meaning that the model allowed for different mean values for each participant. The varying slopes were assigned a prior distribution centred on the grand slope β, and with standard deviation σβ. X represents a categorical variable which includes the various methods of measurement to be compared. Given that the predictor categories from rating scales should not be assumed equidistant with respect to their relationship to the response variable, the distance between adjacent predictor categories are estimated from the data and may vary across categories.

5.3.5 Comparison methods

All the models produced were compared using three methods in the following order of priority: Leave-One-Out cross-validation (LOO), Bayes Factor, Bayesian R^2. Firstly, LOO information criterion (LOOIC) was used to determine the relative predictive performance of the models in terms of pointwise out-of-sample prediction accuracy using log-likelihoods from posterior simulations of parameter values (Vehtari et al., 2017). A model was considered better if it produced a LOOIC difference greater than twice its corresponding standard error. Where a comparison of models using LOOIC does not achieve this level of difference, the second model comparison method was used where Bayes Factors (BF) quantified the support for one model over another. Where a particular model achieved a BF_{10} greater than 10, relative to other models, it was considered the better model. To determine which model was better using LOOIC and then BF, the model with the highest Bayesian R^2 was selected. The Bayesian R^2 is seen as a data-based estimate of the proportion of variance explained for new data (Gelman et al., 2019).

To describe the relationship between walking cadence and %HRR a series of Bayesian regression models were fitted to the data from the MVPA app walking cadence and chest strap ECG heart rate. These modelled walking cadence as a linear function of walking cadence, plus Gaussian noise using a standard linear model, a linear skew normal, 2nd order polynomial and a non-linear smooth model. To determine the best model of the relationship, model fit was determined using the Leave-One-Out cross validation (LOO), a method of estimating pointwise out-of-sample prediction accuracy from fitted Bayesian models using a log-likelihoods from posterior simulations of the parameter values (Vehtari, Gelman and Gabry, 2017). The best model for describing the relationship between walking cadence and %HRR was the non-linear smooth regression.

5.4 Results

Participants provided written consent to undertake a maximal exercise test and the research exercise protocol. Participants had their cardiovascular risk assessed using the ACSM risk classification guidelines prior to participation (Liguori, 2022). Seventy-seven participants were initially recruited and examined for eligibility. All participants were eligible to take part in the study and were initially included. Seventy-four participants (3 non-participation) completed all trials and were included in the study. Reasons for non-completion were lack of time (2) and family bereavement (1).

Table 5.1 Mean (SD) participant demographic data.

	Sex	**Age (years)**	**Body mass (kg)**	**Stature (cm)**	**BMI (kg·m^2)**	**Leg Length (cm)**
Mean (SD)	43% F	30.7 (10.3)	74.06 (14.8)	172.7 (10.1)	24.8 (4.4)	89.2 (6.2)

The mean (SD) for maximal oxygen consumption and resting oxygen consumption as measured using an online gas analysis system, chest strap ECG resting heart rate, 7-day RHR recorded via the Apple Watch, 5 - min MVPA app reading taken during the resting VO_2 protocol, recorded HR_{max} taken from the VO_{2max} protocol and age predicted HR_{max} using the Gellish formula (Gellish et al., 2007) are below.

Table 5.2 Mean (SD) maximal oxygen consumption and resting oxygen consumption.

	VO_{2max} ($mL \cdot kg^{-1} \cdot min^{-1}$)	VO_{2rest} ($mL \cdot kg^{-1} \cdot min^{-1}$)	Chest strap RHR ($beats \cdot min^{-1}$)	7 – day RHR ($beats \cdot min^{-1}$)	MVPA app RHR ($beats \cdot min^{-1}$)	HR_{max} recorded ($beats \cdot min^{-1}$)	Gellish HR_{max} ($beats \cdot min^{-1}$)
Mean (SD)	40 (10)	3.6 (0.6)	63 (9)	60 (7)	64 (9)	184 (11)	186 (7)

Figure 5.1 illustrates the posterior distributions for resting heart rate recordings from the three protocols used. Specifically, the mean effect (ME) and 95% credible interval (CI) for each posterior distribution were, 7 – day protocol ME: 60 CI: 58 to 62 beats·min^{-1}, 5-min protocol ME: 63 CI: 61 to 65 beats·min^{-1} and 30-minute protocol ME: 63 CI: 61 to 65 beats·min^{-1}.

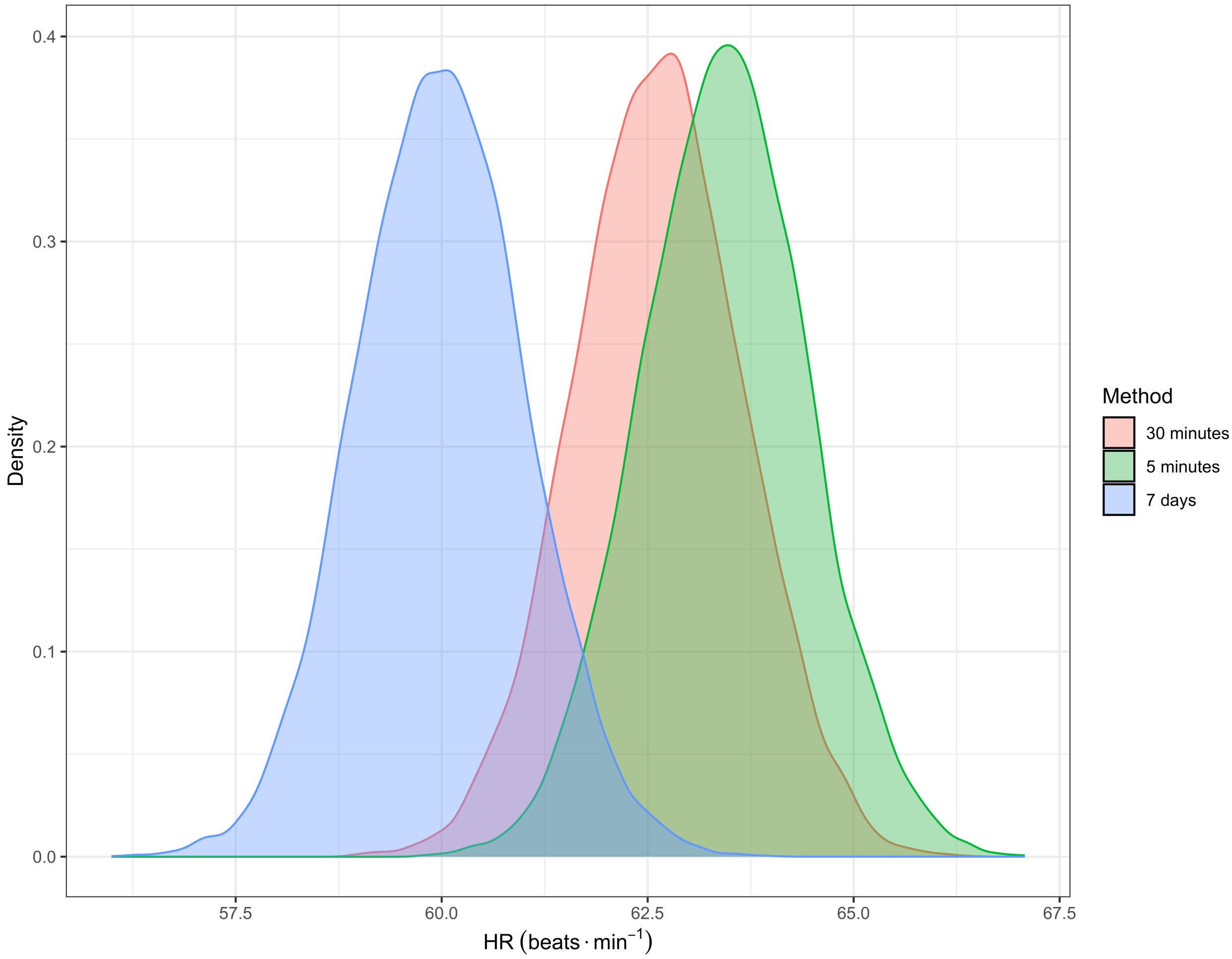

Figure 5.1 Posterior distributions for the measurement of resting heart rate using 30-minute, 5-minute supine laboratory measurements, and 7-day mean from the Apple Watch.

Figure 5.2 illustrates the maximum heart rate protocols from the 2 predictive methods Gellish et al. (2007) and 220 – age, compared to criterion measured HR_{max} taken during the maximal oxygen consumption test. Specifically, the mean effect (ME) and 95% credible interval (CI) for each posterior distribution were, Gellish ME: 185 CI: 182 to 187 beats·min^{-1}, 220 – age ME: 189 CI: 187 to 191 beats·min^{-1} and maximal oxygen consumption test ME: 186 CI: 183 to 188 beats·min^{-1}.

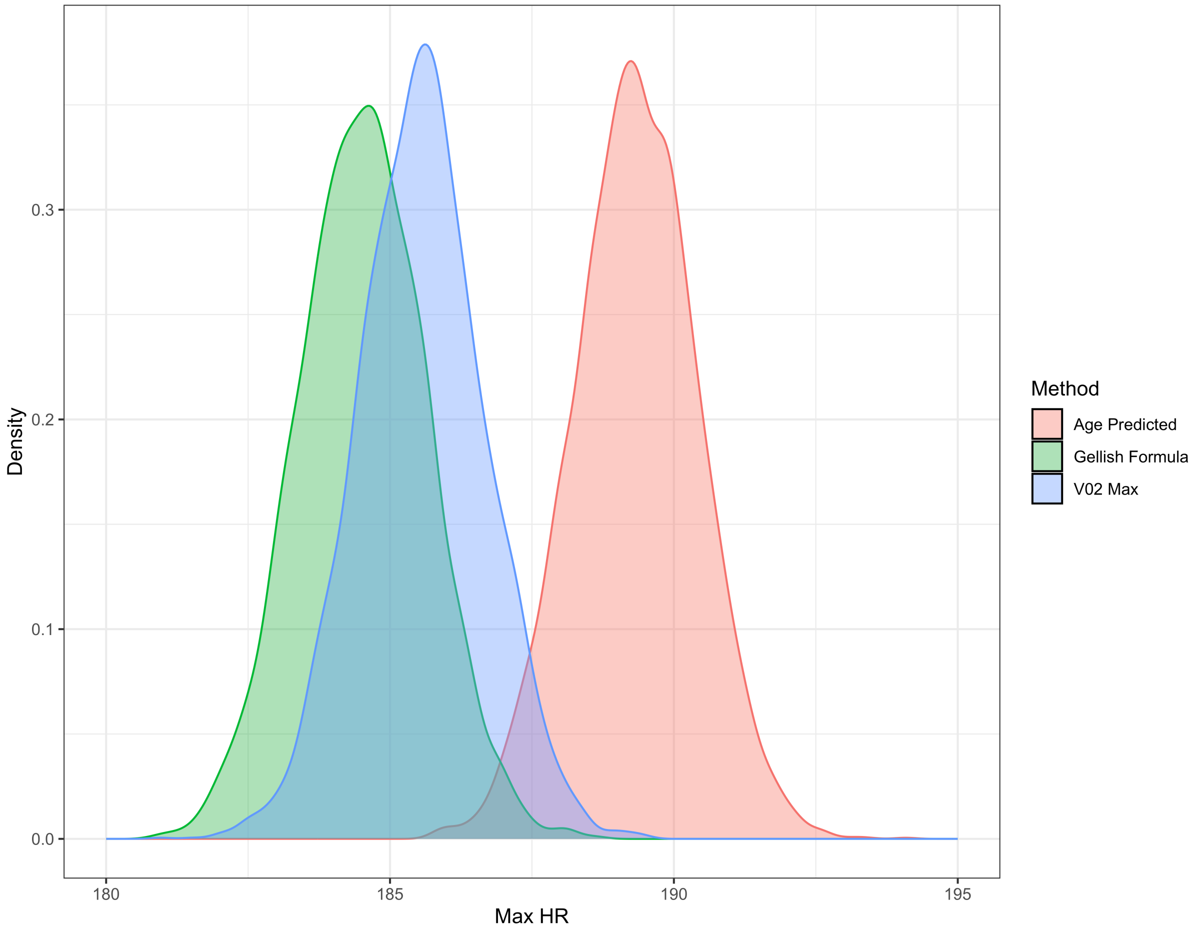

Figure 5.2 Posterior distributions for measured HRmax and predicted HRmax from the Gellish and age-predicted formulas.

Mean (SD) %HRR, %VO_2R and treadmill speed required to advance the Apple Watch green exercise ring by 5-minutes and record 3-minutes of MPA on the MVPA app (reported as the inflection point) are presented in Table 5.3.

Table 5.3 Mean (SD) %VO2R, %HRR and treadmill speed at the inflection point for Apple Watch native app and MVPA app.

Mean (SD)	%VO_2R	%HRR (ECG)	%HRR (watch)	Speed (km·h^{-1})
Native app	33 (10)	33 (10)	34 (10)	5.36 (1)
MVPA app	43 (9)	43 (6)	44 (3)	6 (1)

Mean (SD) %HRR, %VO_2R, treadmill speed and cadence required to meet 3 METS (absolute moderate intensity) are presented in Table 5.4. (METs calculated using the hybrid method described in Chapter 4, measured oxygen consumption divided by 3.5 mL·kg^{-1}·min^{-1}).

Table 5.4 Mean (SD) %VO2R, %HRR, treadmill speed and cadence at 3 METs.

Mean (SD)	%VO_2R	%HRR (ECG)	Cadence steps·min^{-1}	Speed (km·h^{-1})
3 METs	23 (8)	25 (8)	104 (9)	3.8 (0.4)

Table 5.5 displays the posterior distribution mean effect and 95% credible intervals for the 3 MET inflection point for %HRR, %VO_2R, treadmill speed and cadence.

Table 5.5 Mean effect (95% CI) for the 3 MET inflection point for *%HRR, %VO_2R, treadmill speed and cadence.*

Mean effect (95% CI)	%VO_2R	%HRR (ECG)	Cadence steps·min^{-1}
3 METs	22 (20.7 – 23.14)	23.7 (22.6 - 25)	102 (100 – 103)

Figure 5.3 illustrates the oxygen consumption reserve (%VO_2R) at the inflection point for the native Apple Watch exercise ring whereby all five-minutes had been recorded as 'exercise'

and the MVPA app had recorded a minimum of three-minutes of the five-minute bout as criterion moderate intensity. Specifically, the mean effect (ME) and 95% credible interval (CI) for the native Apple Watch activity app were ME: 33.2% CI: 30.8% to 35.5% VO_2R, and the MVPA app, ME: 42.5% CI: 40.3% to 44.4% VO_2R. The Bayesian R^2 value for the MVPA app as a data-based estimate of the proportion of variance at 40% VO_2R was 0.75. For the native Apple Watch activity app Bayesian R^2 was 0.07.

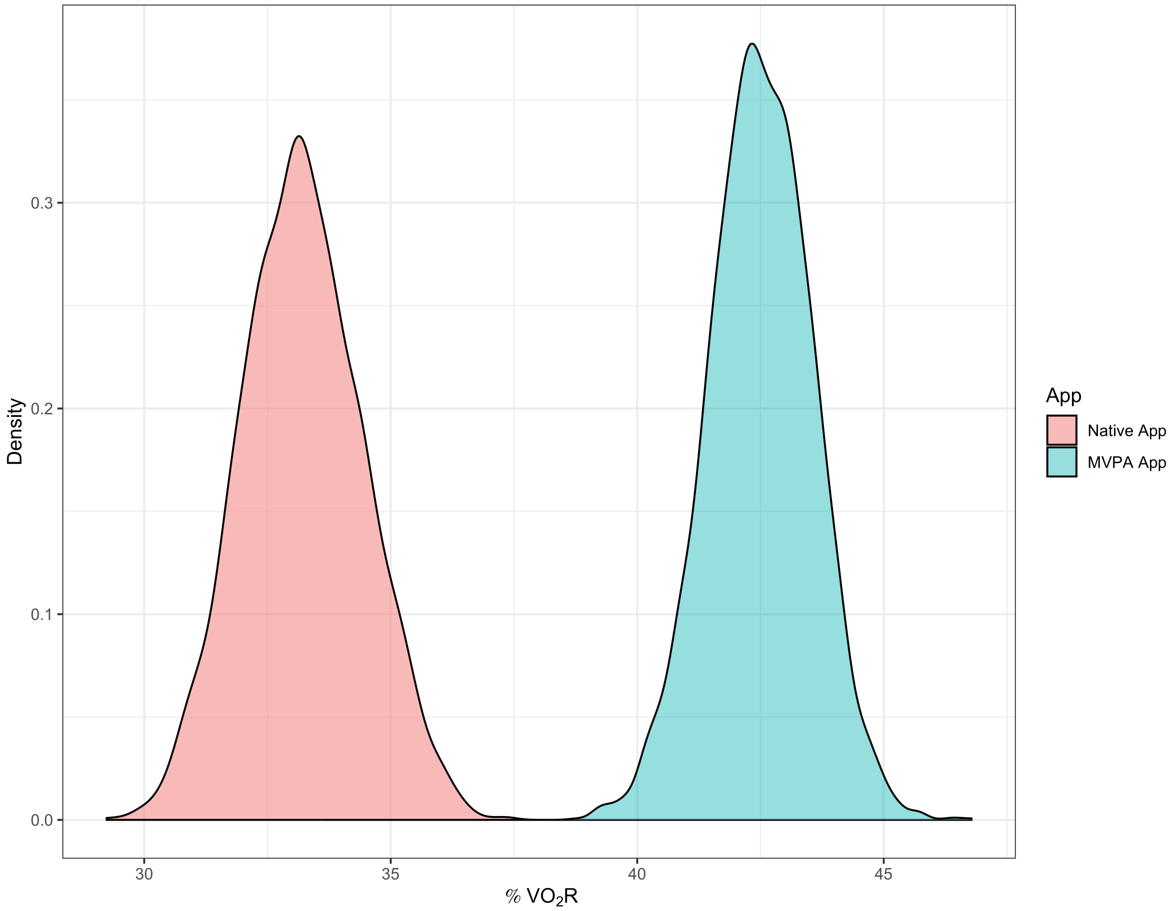

Figure 5.3 Posterior distributions for oxygen consumption reserve (%VO2R) at the inflection point for the native Apple Watch exercise ring and MVPA app.

Figure 5.4 illustrates the % heart rate reserve (%HRR) at the inflection point for the native Apple Watch activity app whereby all five-minutes had been recorded as 'exercise' and the MVPA app had recorded a minimum of three-minutes of the five-minute bout as criterion moderate intensity. Specifically, the mean effect (ME) and 95% credible interval (CI) for the native Apple Watch activity app were ME: 33.2% CI: 31.1% to 35.4% HRR, and the MVPA app, ME: 44.1% CI: 43.4% to 44.8% HRR. The Bayesian R^2 value for the MVPA app as a data-based estimate of the proportion of variance at 40% HRR was 0.64. For the native Apple Watch activity app Bayesian R^2 was 0.015

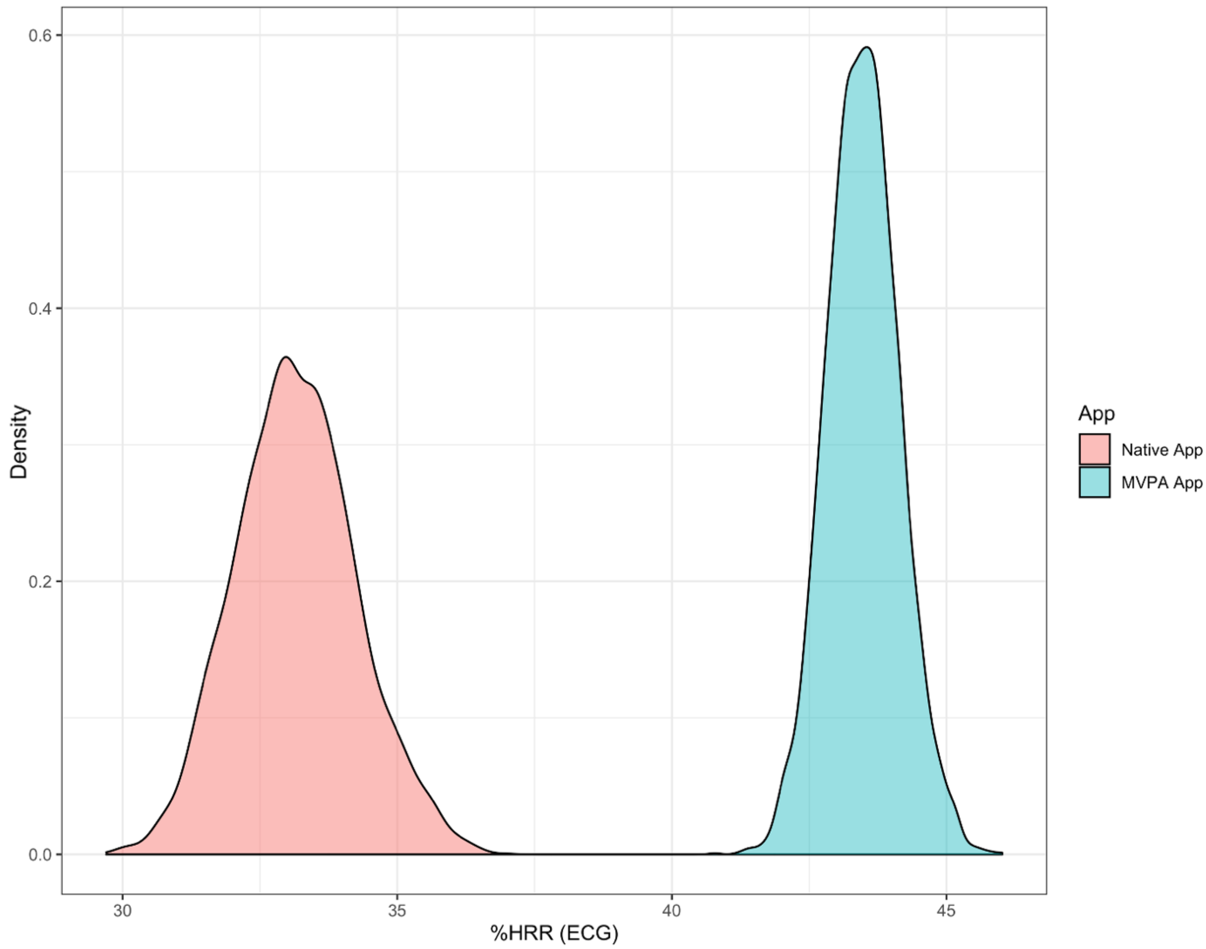

Figure 5.4 Posterior distributions for % heart rate reserve (%HRR) at the inflection point for the native Apple Watch exercise ring and MVPA app, heart rate from the ECG chest strap.

Figure 5.5 illustrates the Bayesian regression model for walking cadence and %HRR. The curvilinear relationship found between %HRR and walking cadence estimated by the Apple Watch can be best described by a non-linear smooth regression. The model predicts that the mean (95% CI) walking cadence required to elicit 40% HRR is 123 (120 – 126) steps·min^{-1}.

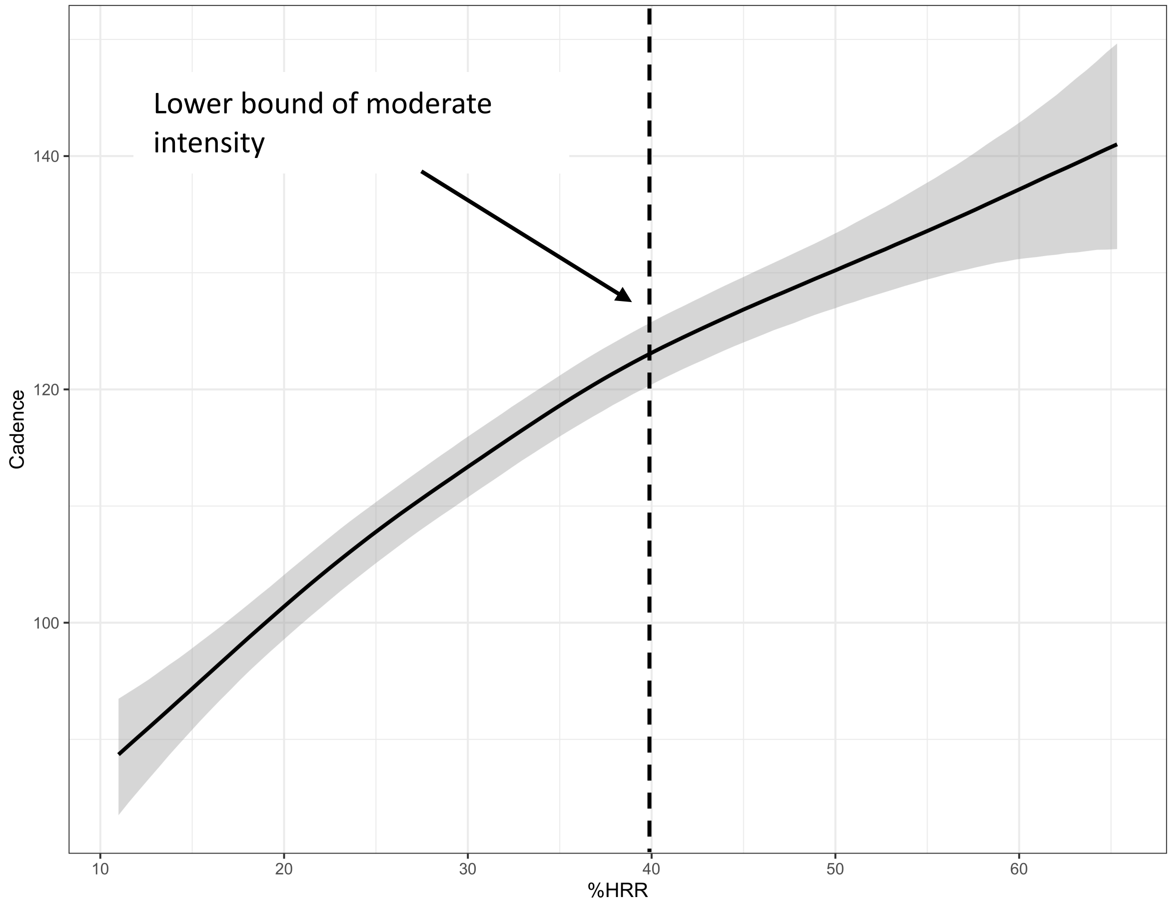

Figure 5.5 The curvilinear relationship observed between walking cadence and %HRR taken from the Apple Watch. Grey shaded area is the 95% credible interval.

5.4.1 Subjective measures

The mean (SD) subjective measures given at the inflection point for the MVPA are reported in Table 5.6 For reference, RPE 'moderate' intensity is identified as three on the scale. Thermal sensation 'moderate' intensity is identified as eight, 'slightly warm' on the scale, and breathlessness 'moderate' identified as three on the scale. The talk test was correctly identified as 'not easy' at the inflection speed for the MVPA app in 18% of trials.

Table 5.6 The mean (SD) scores for each subjective measure at the inflection point as reported by the MVPA app (40% HRR)

Subjective measure	**RPE**	**Thermal sensation**	**Breathlessness**
Mean (SD)	3 (0.9)	8.3 (1.4)	1.9 (1.1)

Figure 5.6 illustrates a Bayesian regression model of RPE and corresponding %HRR from the ECG chest strap. The point estimate (95% CI) for RPE at 40% HRR was 3.2 (CI: 1.8 to 5.4). The point estimate for %HRR at 3 RPE was 40.52% (CI: 23.33% – 57.42%) HRR. The Bayesian R^2 value for RPE as a data-based estimate of the proportion of variance at 40% HRR was 0.16.

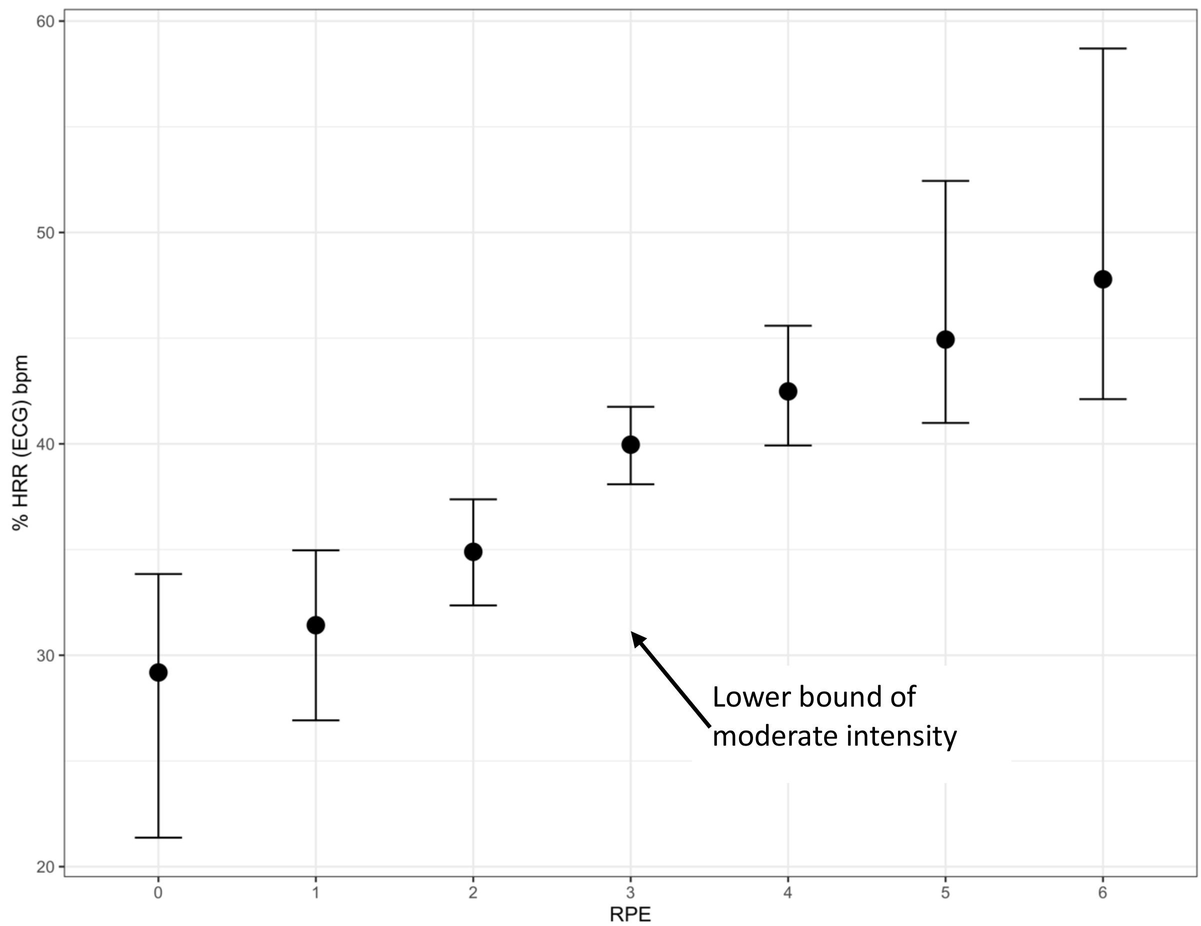

Figure 5.6 Bayesian regression model of RPE and corresponding %HRR (95% credible interval) from the ECG chest strap.

Figure 5.7 illustrates a Bayesian regression model of thermal sensation and corresponding %HRR from the ECG chest strap. The point estimate for %HRR at 8 thermal sensation was 39.2% (CI 21.5% – 57.5%) HRR. The Bayesian R^2 value for thermal sensation as a data-based estimate of the proportion of variance at 40% HRR was 0.12.

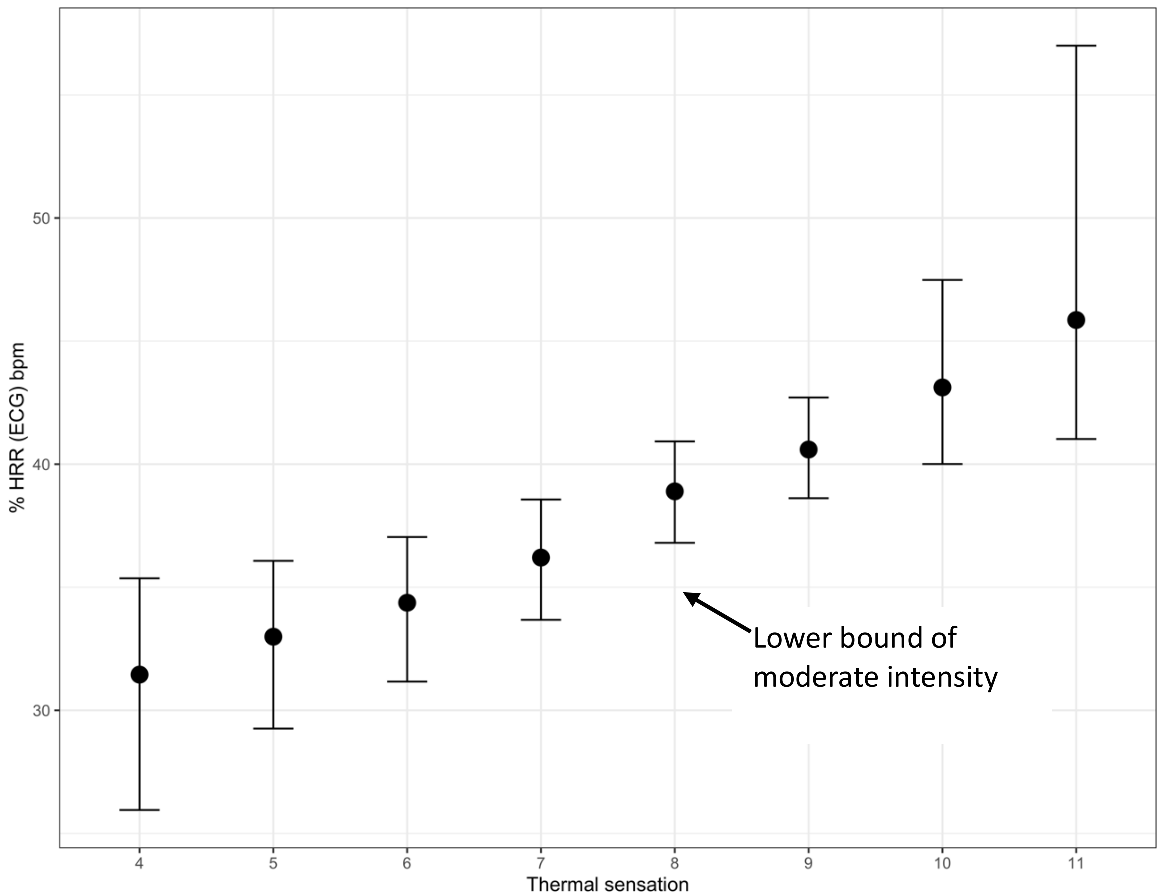

Figure 5.7 Bayesian regression model of thermal sensation and corresponding %HRR (95% credible interval) from the ECG chest strap.

Figure 5.8 illustrates a Bayesian regression model of breathlessness and corresponding %HRR from the ECG chest strap. The point estimate for %HRR at a breathlessness of 3, was 42.4% (CI 24.8% – 59.7%) HRR. The Bayesian R^2 value for breathlessness as a data-based estimate of the proportion of variance at 40% HRR was 0.14.

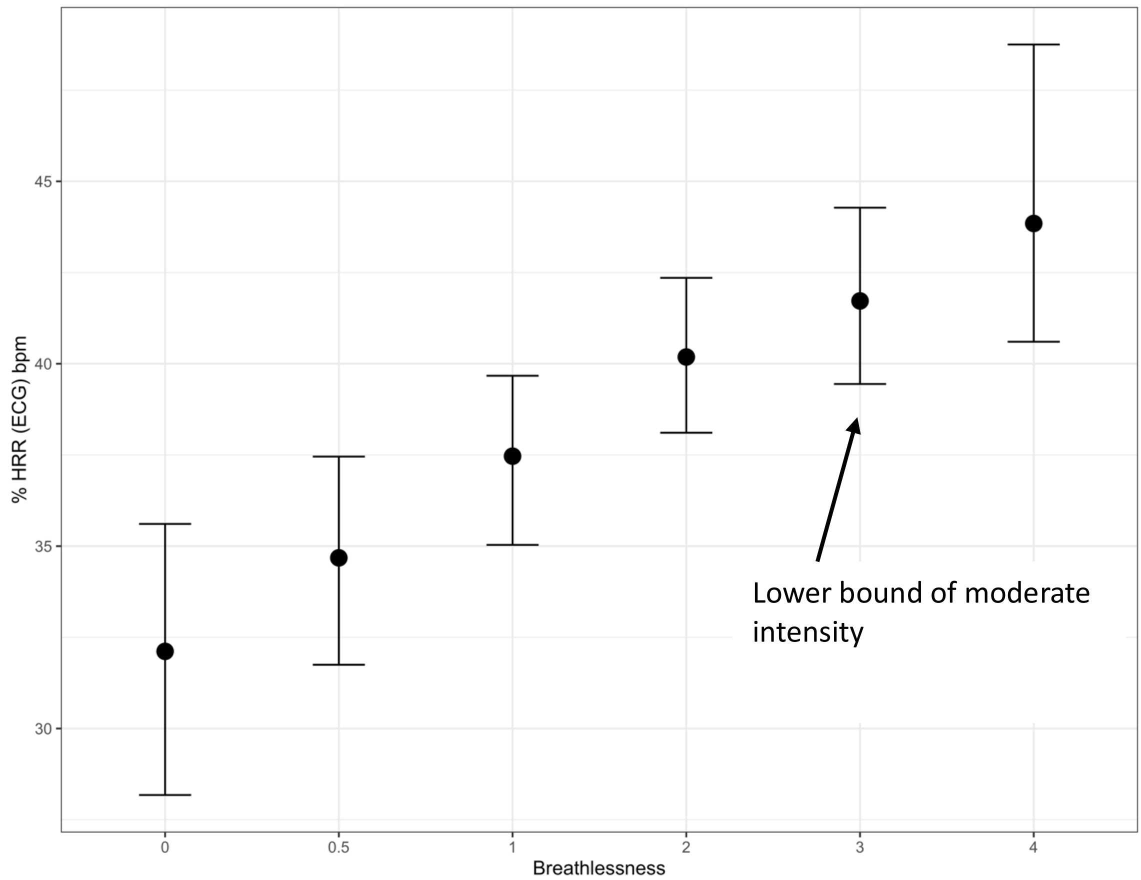

Figure 5.8 Bayesian regression model of breathlessness and corresponding %HRR (95% credible interval) from the ECG chest strap.

There was one deviation from the pre-registration reported and one additional analysis conducted. For the subjective scales a monotonic regression was published in the pre-registration. However, on analysis of such measures a posterior distribution was conducted to ensure all variables were based on the model and not future predictions. This allowed for a comparison between objective and subjective variables to be conducted comparatively. Additionally, a Bayesian regression was conducted between walking cadence and %HRR to encapsulate the required walking cadence to elicit moderate intensity.

5.5 Discussion

5.5.1 MVPA app vs the Apple Watch exercise ring

The main finding of this study is that using %HRR more accurately measures moderate intensity than the Apple Watch activity app when compared with the criterion, %VO_2R. The mean (95%CI) %HRR for the MVPA app and Apple Watch Activity app were 42.5% (40.3% to 44.4%) and 33.2% (30.8 to 35.5%), respectively. These data show that at the point both apps (bespoke MVPA and native Activity) suggested that participants were exercising at moderate intensity, only the bespoke MVPA app achieved this criterion, with the native Apple Watch Activity app intensity being well below the 40% HRR threshold. Moreover, the entire posterior distribution for the native Activity app was outside the pre-registered ROPE, suggesting that this effect is a meaningful one.

It was also shown that the Apple Watch 'exercise' ring largely underestimates the walking cadence required to elicit the lower bound of moderate intensity (40% VO_2R) (Figure 5.3). Given this result, %HRR may be the most accurate and accessible individualised measure of exercise intensity that can be incorporated into a wrist-worn wearable device. Given the popularity of wearable devices (*Global connected wearable devices 2016-2022*), the ability to scale individualised measurement of moderate (and vigorous) exercise intensity at a population level should not be underestimated. The posterior distributions comparing the MVPA app with the Apple Watch native app highlights that using %HRR is more likely to measure physical activity intensity of moderate or above (40% VO_2R) more accurately compared to the Apple Watch native app, which was unlikely to measure intensity accurately compared to criterion intensity %VO_2R. These findings are in line with previous investigations (Abt, Bray and Benson, 2018; Abt et al., 2019), highlighting the need for individualisation of exercise monitoring using relative intensity, given that physical activity intensity is influenced by fitness status. For example, in the current study the minimum treadmill speed required to elicit MPA for an individual (40% HRR) by the MVPA app was 3.5 $km \cdot h^{-1}$ while the fastest treadmill speed required to reach MPA for an individual was 8.0 $km \cdot h^{-1}$. This highlights the individualised nature of the intensity spectrum and how the participants CRF plays an integral role in the speed required to elicit MPA. However, while CRF plays an integral role in the walking cadence required to meet a relative measure of moderate intensity (Abt et al., 2019), when physical activity is monitored relatively via a physiological measure such as %HRR and thus individualised via intensity thresholds, the need for a walking cadence prescription is only useful when walking is performed in short bursts, where the delay in heart rate response does not allow for physiological mechanisms to be measured relatively. Although previous studies have monitored/promoted physical activity via step count (typically 10,000 steps per day, or 3,000 steps in 30 minutes, 100 $steps \cdot min^{-1}$) (Le-Masurier, Sidman and Corbin, 2003; Tudor-Locke et al., 2005; Marshall et al., 2009), using a relative measure of physical activity intensity as shown in the current study, is a more accurate measure of physical activity intensity. And although the use of relative intensity has previously not been feasible at scale (population level), developments in wearable technology now allow access to real-time relative intensity data (e.g., %HRR). The growing popularity of wearable devices now makes this individualised approach a reality, and at scale. In recent years the global wearables market has seen seismic growth, with active wearable device users tripling from 325 million in 2016 to 1.1 billion in 2022 (Statista, 2023). Ultimately, the use of individualised relative intensity measures for physical activity monitoring and prescription has potential implications for mortality and morbidity risk. As previously mentioned CRF plays an integral role in accurately prescribing and monitoring individualised physical activity intensity. Essentially the higher an individual's CRF is, the faster the cadence required to reach moderate intensity physical activity when walking (Abt et al., 2019). Ensuring participants accumulate physical activity more accurately at relative moderate intensity will improve cardiovascular health, and should in theory, reduce all-cause mortality while also reducing morbidity risk such as type 2 diabetes, CV disease and stroke (Al-Mallah, Sakr and Al-Qunaibet, 2018).

Measuring physical activity accurately on a population scale is complex. However, based on the findings from the current study, the Apple Watch would overestimate MVPA when compared to measuring MVPA using the criterion %VO_2R (or %HRR). Mean treadmill speed at which the Apple Watch registered physical activity on the green 'exercise' ring was 0.8 $km \cdot h^{-1}$ slower than the MVPA app. The Apple Watch also recorded 'exercise' on the green ring at a mean intensity of 33% VO_2R, compared to the MVPA app which recorded moderate physical activity at a mean of 43% VO_2R. Currently, the Apple Watch records physical activity via an accumulation of accelerometery data and intermittent heart rate data (Apple, 2022) This is likely configured to prolong battery life of the wearable device, as using the PPG sensor continually requires additional battery power. Therefore, as a relative measure of intensity is not used regularly it is likely overestimating physical activity, because the Watch is measuring physical activity mostly via an absolute accelerometery measurement. Additionally, the point at which 3 METs was recorded, (obtained using the hybrid method described in Chapter 4), whereby oxygen consumption is divided by an arbitrary resting oxygen consumption value of 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$ also indicates a substantial overestimation of physical activity intensity when compared to criterion %VO_2R (or %HRR). At 3 METs, %HRR mean (SD) was 25% (8) and %VO_2R was 23% (8) substantially under the 40% moderate intensity boundary. Additionally, cadence was 104 (9) steps·min^{-1} which may indicate why 100 steps·min^{-1} has been advocated as the walking cadence required to elicit moderate intensity (Tudor-Locke et al., 2018; Aguiar et al., 2019). However, the findings of the current study suggest that using %HRR that takes into consideration two measures of physiological capacity (resting HR and maximal HR), is likely to measure physical activity intensity more accurately on an individual basis. Given the potentially large overestimation of MVPA throughout the day when using the Apple Watch exercise ring, a greater degree of personalisation is required. The need for personalisation of exercise intensity thresholds requires either a more continual use of background heart rate measurements by the Apple Watch during everyday ambulation, or a greater personalisation of data (feedback) given to users to ensure walking cadence meets relative moderate intensity thresholds. At current the Apple Watch has heart rate zones for physical activity displayed in the workout app (Monitor your heart rate with Apple Watch - Apple Support) that are based on %HRR. However, the default zone 1 begins at 60% HRR, or vigorous intensity as defined by the ACSM (Liguori, 2022). Moreover, these zones and the monitoring of exercise via %HRR are not used to identify exercise on the exercise ring displayed in the Activity app during everyday ambulation, or when an exercise mode is selected in the Workout app. Although heart rate zones can be modified manually, it is unlikely that Apple Watch users will change the zones to replicate ACSM guidelines (Liguori, 2022). Moreover, starting the first heart rate zone at vigorous intensity is unlikely to increase adherence to exercise (Ekkekakis and Biddle, 2023). As such, the default Apple Watch heart rate zones would benefit from being aligned to the moderate and vigorous exercise intensity guidelines recommended by the ACSM

(Liguori, 2022), by setting zone 1 (moderate intensity) as 40-59% HRR and zone 2 (vigorous intensity) as 60-90% HRR.

5.5.2 Walking cadence required to elicit moderate intensity.

The mean effect (95% CI) walking cadence required to reach the lower bound of relative moderate intensity (40% HRR) in this study was 123 (120 to 126) steps·min^{-1}. This is substantially higher than the current heuristic recommendation of 100 steps·min^{-1} for walking cadence required to elicit the lower bound of moderate intensity published in the literature (Tudor-Locke et al., 2018). It is likely the 100 steps·min^{-1} target is obtained from the cadence required to reach 3 METs, as indicated from this study's findings this is approximately 20% lower than the cadence required to reach criterion %VO_2R (or %HRR) and is substantially overestimating moderate intensity. Additionally, a previous investigation from our research group highlighted the impact that fitness status (CRF) has on the walking cadence required to reach relative moderate intensity (% VO_2R) (Abt et al., 2019), with a mean of 140 steps·min^{-1} required. Although this value is higher than the mean walking cadence required to reach MPA found in the current study (123), it is likely impacted by the higher fitness status of the participants [VO_2max 45 (10) mL·kg^{-1}·min^{-1}] compared to the participants in the current study [VO_2max 40 (10) mL·kg^{-1}·min^{-1}]. Additionally, the lower sample size of 20 may have also impacted results (Abt et al., 2020). Nevertheless, the results of these two studies combined highlights the need to individualise exercise prescription and monitoring as fitness status plays an integral role in the cadence required to elicit the lower bound of relative moderate intensity. This also emphasises the need to reduce the reliance on target step counts as a dependable measure of MPA, as the variability in cadence required to reach moderate intensity varies dramatically depending on fitness status. Although there is undeniable benefit in step count targets, such as the association with a reduced risk of mortality and co-morbidities (Brown, Harhay and Harhay, 2014; Paluch et al., 2022), based on the findings of the current and previous studies (Serrano et al., 2017; O'Brien et al., 2018; Abt et al., 2019), people working towards step count targets might not be completing physical activity at a high enough cadence to maximise cardiorespiratory benefit. And although there could still be some cardiometabolic benefit from performing light intensity exercise, a recent meta-analysis of 72 studies (Chastin et al., 2019) suggested that while light intensity may help control postprandial glucose and insulin sensitivity compared to sedentary behaviour, definitive conclusions on light intensity exercise affecting other cardiometabolic markers has limited evidence and definitive conclusions could not be drawn. Additionally, physical activity guidelines have placed greater emphasis on the need for moderate intensity physical activity (WHO, 2020; nhs.uk, 2022) and while this is the case, accurate measures and prescription of moderate intensity physical activity are required.

5.5.3 Resting heart rate

Accurate measurement of resting heart rate is important if relative measures of intensity are to be used, and trusted, in wearable devices. Although a 12-lead ECG measurement of RHR is seen as the gold standard (Bayés de Luna et al., 2012), there are obvious practical implications for using this method outside of laboratory conditions. The resting heart rate data measured in the current study demonstrates that in comparison to the criterion 30-minute supine recorded RHR, the 5-minute protocol embedded in the MVPA app overestimates mean RHR by ~1 beats·min^{-1} [Cohen's *d*], while the mean 7-day Apple Watch estimate seems to underestimate RHR by ~3 beats·min^{-1} [Cohen's *d*]. These results have implications for real world app useability and subsequent physical activity monitoring via wearable technology. First, it is unlikely that wearable device users would be willing to maintain a supine position for a period (either 30-minutes or 5-minutes) while heart rate is recorded. Second, although the underestimation of RHR using the 7-day Apple Watch data may result in slightly different %HRR measurements, this effect might be trivial in practice. For example, the data displayed in Figure 5.3 showing the posterior distribution of %HRR for the MVPA app is based on the use of the 7-day RHR data from the Apple Watch, and yet this distribution matches quite closely that displayed for $\%VO_2R$ (Figure 5.3). Moreover, the difference in HRR at 40% between a RHR of 60 and 63 for a person with a HRmax of 200 is 2 beats·min^{-1}. So, the use of background RHR as recorded automatically by the Apple Watch might represent a ’sweet spot’ balance between convenience and accuracy.

There is evidence that wearable devices have the capacity to accurately measure heart rate, especially during rest (Georgiou et al., 2018). As the wearable device is able to continually monitor resting heart rate, there is an increased opportunity to obtain data and thus possibly obtain a better estimation of RHR as devices take multiple measurements throughout the day. However, we have found that RHR measured over seven days using the Apple Watch resulted in an underestimation of criterion RHR obtained from a 30-minute laboratory protocol. As discussed above though, this underestimation might not have a practical effect on %HRR measurement and might represent a balance between convenience and accuracy.

While at current to the best of the authors knowledge there are no studies investigating the validity of recording resting heart rate via the Apple Watch compared to ECG at rest, a recent investigation (Ho, Yang and Li, 2022) recorded resting heart rate via an Apple Watch and ECG during 3 minutes of seated rest prior to a maximal oxygen consumption protocol. The mean absolute percentage error between Apple Watch and ECG was 1.7%. The Apple Watch's useability in measuring health and physical activity may have a wider impact than the prescription of exercise intensity. For example, Greiwe and Nyenhuis (2020) suggest that telemonitoring of health measures (such as RHR) may transform the way health is measured and diagnosed.

5.5.4 Maximal heart rate

The posterior distributions of HR_{max} (Figure 5.2) indicates that the Gellish formula (Gellish et al., 2007) was the most accurate at predicting HR_{max} (~ 1 beats·min^{-1} difference) while the 220 - age calculation overestimated HR_{max} (~ 4 beats·min^{-1} difference) compared to the criterion measured during a maximal oxygen consumption test. These findings are in line with previous studies (Machado and Denadai, 2011; Nes et al., 2013; Sarzynski et al., 2013) reporting that 220 - age did not accurately predict HR_{max}. In order to prescribe and monitor exercise intensity more accurately, an upper (HR_{max}) and lower (RHR) bound of heart rate is required to quantify intensity thresholds using %HRR (Dalleck and Kravitz, 2006; Lounana et al., 2007). These findings have important implications in a real-world setting. The likelihood of individuals performing maximal oxygen consumption testing is very low, therefore predictive measures are often used to calculate maximal values. Based on the findings of this study, those predictions should use the Gellish et al. (2007) formula as it more closely aligns with the HR_{max} recorded during the maximal oxygen consumption testing performed in this study.

5.5.4 Subjective measures

Although wearable technology may possess the ability to accurately identify exercise intensity, it is not always plausible to use objective measures of physical activity. Equipping individuals with adequate tools to assess individual intensity, subjectively, during exercise is important in the prescription and monitoring of physical activity intensity when wearable devices are not available. It is also of importance to understand the usefulness of such subjective tools to better define guidelines for physical activity intensity. Subjective measures are also touted as ways for the public to gauge when they are engaging in 'moderate' intensity, for example, by the UK NHS.

Based on the Bayesian regression models constructed (figure 5.6), an RPE of 3 aligned with objectively measured MPA from %HRR. The 95% credible interval for %HRR at an RPE of 3 was 23.33% – 57.42%. Although the point estimate (40.52% HRR) probably suggests that RPE is a useful tool for gauging physical activity intensity, the 95% credible interval associated with this relationship suggests that it there is large inconsistency in using RPE to gauge physical activity intensity. Additionally, the Bayesian R^2 value (0.16) indicates RPE to be a poor indicator of moderate intensity. So, although the mean response suggests that an RPE of 'moderate' would allow people to reach 40% HRR, the distribution of effects would suggest that some people will require an RPE higher than 3 to achieve 40% HRR. Several authors have employed different subjective measures of physical activity intensity (lactate threshold [LT], heart rate, maximal oxygen uptake) and exercise modalities (cycle ergometer, treadmill walking and running) to understand the usefulness of RPE in subjectively measuring physical activity intensity (Eston, Davies and Williams, 1987; Shigematsu et al., 2004; Scherr et al., 2013). The largest known study comparing RPE (Borg scale) with metabolic (lactate concentrations) and cardiac (heart rate) intensity thresholds investigated the accuracy of RPE in 2,560 adults of which 146 were coronary artery disease patients (Scherr et al., 2013). Participants performed an incremental exercise test on either a treadmill or cycle ergometer, with protocols increasing the intensity of exercise every three minutes by 1-2 $km \cdot h^{-1}$ on the treadmill and by 20 - 50 W on the cycle ergometer. Linear regression revealed a high correlation between RPE and lactate thresholds (r^2 = 0.71) whereas the relationship between heart rate and RPE was lower (r^2 = 0.55). Although the study by Scherr et al. (2013) reported a good correlation between RPE and lactate threshold, the correlation between heart rate and RPE is moderate, with approximately 50% of the variance in HR explained by RPE. Overall, this would suggest that an RPE of three is generally associated with relative moderate intensity, but the high variance in %HRR at a three RPE in this study suggests it may not be useful in gauging physical activity intensity.

The results of the Bayesian regression model highlighted that at the lower bound of moderate intensity (based on 40% HRR), participants rated their breathlessness at three, which corresponds to 'moderate' on the breathlessness scale. Moreover, given the 95% credible interval at three was 24.8% to 59.6% HRR (Figure 5.8), suggests that it there is large inconsistency in using breathlessness to gauge physical activity intensity. Additionally, the Bayesian R^2 (0.14) indicates breathlessness to be a poor indicator of moderate intensity with a high-level variance compared to %HRR. Although breathlessness has been identified as a useful indicator of intensity in clinical populations (Mahler et al., 1991; Jensen et al., 2008; Guenette et al., 2011), data on its use in healthy people is scarce. Authors have used modified Borg category ratio RPE (Borg, 1982) to assess dyspnoea (shortness of breath) during exercise in healthy populations (Jensen et al., 2011) where participants were informed;

"0 represented no breathing discomfort and 10 represented the most severe breathless discomfort you have ever experienced or could ever imagine experiencing" (Jensen et al., 2011 p 221).

In the study by Jensen et al. (2011), Borg rating of breathlessness was associated with subjective intensity, where participants' breathlessness was rated higher during a 500 mL dead space loading compared to control conditions, suggesting subjectively, breathlessness may be a good indicator of exercise intensity. Additionally, Jensen et al. (2009) reviewed the literature on ventilatory reserve and associated breathlessness in healthy, pregnant and overweight populations. Authors referred to a modified RPE breathlessness scale (defined as Borg's rating of perceived breathlessness). Use of the Borg breathlessness scale indicated that participants were able to identify an increased perception of exertional breathlessness during exercise. However, while breathlessness has been highlighted as a subjective measure with potential, its validity as a measure of exercise intensity thresholds has not been investigated. While health service providers refer to breathlessness as a form of quantifying moderate intensity (nhs.uk, 2022), its useability may need wider validation. A recent review, on the standardisation of breathlessness measurement during exercise called for a direct assessment of breathlessness that abides by the principles of psychophysics, such that a standardised stimulus is used to evaluate the sensation of breathlessness, allowing for controlled exercise environments. This would allow breathlessness to be linked to the corresponding exercise intensity (Lewthwaite et al., 2019). Additional validation of a breathlessness scale to subjectively quantify physical activity intensity in healthy populations is warranted.

Thermal sensation was found to slightly underestimate moderate intensity, i.e., participants perceived themselves to be 'slightly warm' on the thermal sensation scale at less than 40% HRR. However, the 95% credible interval for %HRR (Figure 5.7) at a thermal sensation of 8 was 21.5% to 57.52% HRR, spanning very light intensity to near the upper bound of moderate intensity. As for breathlessness, the NHS guideline that people should "feel warmer" when engaging in moderate intensity physical activity appears to be an underestimation. A number of authors have used thermal sensation and thermal comfort as a subjective measure of exercise intensity in a number of different environments, from extreme conditions (hot and cold) (Schlader et al., 2011; Schulze et al., 2015) to optimum commercial gym temperatures for exercise (Huang et al., 2021). Thermal subjective scales are often used in temperature affected environments, to subjectively measure the impact external temperature has on subjective feeling and subsequent perception of exercise intensity (Huang et al., 2021; Lin, Jin and Jin, 2022). A number of authors have advocated thermal sensation and thermal comfort as likely perceptual modulators of exercise intensity (Schlader et al., 2011; Koelblen et al., 2018). Its use as a subjective measure of exercise intensity under normal conditions has not been extensively researched, especially as a tool for identifying physical activity intensity thresholds. However, while extensive research in this area does not exist, government guidelines refer to body temperature as guidance for moderate intensity physical activity (nhs.uk, 2022). Although it is common knowledge that body temperature rises during physical activity (Jose, Stitt and Collison, 1970; Gleeson, 1998), its applicability to subjectively gauge intensity from an increase in subjective body temperature is unknown. It is important that claims of using subjective body temperature are tested because a wide range of external factors impact body core temperature, including air temperature, air velocity, radiant temperature, relative humidity, insulation of clothes, and metabolic rate (Kim, Shin and Cho, 2021), which may all impact peoples' ability to correctly identify MPA from thermal sensation. Another important element of using thermal sensation as a subjective measure of exercise intensity is sensation delay. That is, the delay between the commencement of physical activity and a change in subjective sensation of warmth. The human body usually takes several minutes of physical activity before a sensation of 'warmth' is registered (Wenger, 1995). This has implications for brief bouts of moderate intensity physical activity, such as brisk walking that only lasts a few minutes in duration. Typically, the heart rate response during these brief bouts is quicker than the thermal response (Cheng et al., 2008), so this needs to be considered when advising people to use thermal sensation as a tool for gauging moderate intensity.

The talk test is an inexpensive tool for guiding exercise intensity that can be used in a wide range of populations, from elite athletes to those with cardiovascular disease (Reed and Pipe, 2014; Woltmann et al., 2015). It's use at a population level is favourable as it is convenient, and useful from a healthcare professional perspective as a means of gauging exercise intensity and educating subjective feeling toward aerobic physical activity. Due to these reasons, it has been adopted in government guidelines promoting moderate intensity physical activity (nhs.uk, 2022). The foundation of the talk test is that when exercising above ventilatory threshold, conversational speech is no longer comfortable and thus the test serves as a means of estimating a cut point between moderate and vigorous intensity (Reed and Pipe, 2014). In the current study participants correctly identified moderate intensity via the talk test in only 18% of trials. That is, when %HRR recorded via the MVPA app was 40% or above, participants identified performing the talk test as ‘not easy.’ These findings conflict with the current literature that suggests more often than not, the talk test is a useful tool for gauging exercise intensity (Jeans et al., 2011; Reed and Pipe, 2014; Woltmann et al., 2015; Foster et al., 2018b). However, as highlighted by Reed and Pipe (2014) in their review, the ability to converse with ease highlights the ventilatory threshold which, according to the authors, is the point at which moderate intensity becomes vigorous. Additionally, Foster et al. (2018) assessed %HRR among other physiological variables of exercise intensity and the applicability of the talk test to distinguish physical activity intensity thresholds. Participants were able to accurately identify via a talk test the point at which physical activity became vigorous intensity (60% HRR) based on the ACSM intensity guidelines (Liguori, 2022).

The current study has identified the useability of the talk test to predict relative moderate intensity, which is likely to be below the second ventilatory threshold and according to ACSM physical activity intensity guidelines is 40% HRR (Liguori, 2022). This is likely why its use in identifying moderate intensity based on the current study’s findings, is not accurate, as moderate intensity is likely to be below the second ventilatory threshold. However, government guidelines use talking as a means of distinguishing moderate intensity physical activity (nhs.uk, 2022). Therefore, it is important to understand a person’s ability to talk and its applicability at this intensity threshold. Current NHS guidelines for moderate intensity suggest people should be able to ‘talk but not sing,’ when performing MPA. Participants in the current study were able to comfortably talk at an intensity below moderate intensity, with 100% of trial stages performed below 40% HRR coinciding with participants identifying the talk test as ‘easy’. However, as previously stated, 18% of trials performed over 40% HRR were identified as ‘not easy to talk’, which when compared to other study findings is significantly below the point at which exercise becomes vigorous. Nearly one in five participants identified moderate intensity as ‘not easy to converse’, which may contradict its applicability for identifying vigorous intensity as previously described (Reed and Pipe, 2014; Foster et al., 2018b). The singing component of the guidelines might therefore be of greater significance in subjectively interpreting the point at which moderate intensity occurs, as the current bed of literature evidences the talk test as identifying the point at which moderate intensity changes to vigorous intensity (Reed and Pipe, 2014; Woltmann et al., 2015; Foster et al., 2018b). The findings of the current study identify that one’s ability to talk does not accurately coincide with objective, relative moderate intensity physical activity. However, to the best of the author’s knowledge there is no research identifying a person’s ability to sing as guidance for identifying the threshold between light and moderate intensity. Yet, the physiological demands of singing have been investigated (Philip et al., 2021), and while the only variable identified by authors as relatable to intensity thresholds associated with ACSM guidelines (Liguori, 2022) was METs, there is evidence that singing produced similar physiological responses as brisk walking (6 $km \cdot h^{-1}$), which may indicate why NHS guidelines incorporate a singing component within the guidelines for moderate intensity. However, the findings reported by Philip et al. (2021) are limited by the absolute intensity variables used to distinguish physical activity intensity and is likely underpowered (8 participants). Moreover, in relation to NHS guidelines, it does not determine whether singing is a useful subjective measure to gauge exercise intensity, and to the best of the author’s knowledge there is no research indicating a sing test as a useable tool to distinguish physical activity intensity thresholds.

Overall, while the talk test may be useful in identifying the point at which associated physical activity intensity moves from moderate to vigorous in comparison to percentage intensity thresholds, or the point at which the second ventilatory threshold occurs, based on the findings of the current study its appropriateness for identifying the minimum required physical activity intensity for health benefits (moderate intensity) for the general population is limited. Moreover, for a large portion of the general population who do not currently meet physical activity guidelines, using the talk test as a means of encouraging them to subjectively quantify the correct intensity is likely to induce an intensity that is too vigorous and not sustainable for most people (Ekkekakis and Biddle, 2023). Although the inability to sing may give additional guidance and lower the intensity people perform at compared to using the talk test alone, its useability in the general population is questionable. It is unlikely that while performing physical activity in public that people are going to start singing aloud to assess their physical activity intensity. Additionally, evidence for its application as a tool for guiding any form of physical activity intensity does not exist and its inclusion in government guidelines seems questionable. Additional research on its validity as an assessment tool for physical activity is therefore, required.

5.6 Study Limitations

Whilst this study has focussed on using %HRR that can be measured by wearable devices and is therefore accessible to the general population, there are limitations in using this method, that are worth noting. Whilst %HRR is individualised to an extent, they use fixed percentage boundaries to define intensity categories, e.g., moderate intensity is defined at 40 – 59% HRR. Physiological markers such as lactate or ventilatory thresholds may offer a more individualised and subsequent better method of monitoring physical activity intensity as they reflect a real physiological threshold for each individual (IANNETTA et al., 2020). Additionally, ventilatory thresholds have been reported to better anchor physical activity intensity as the metabolic stimulus is better normalised across people with varying fitness levels (WEATHERWAX et al., 2019). However, currently wearable devices do not have the ability to measure such physiological thresholds, and therefore, at current %HRR may currently offer the most accurate relative measure available at a population level. Additionally, the ROPE used to define the lower bound of moderate intensity in this study are defined from previous literature (Abt et al., 2019). However, there is evidence to suggest a lighter intensity, defined as 30 – 40% HRR in ACSM guidelines (Liguori, 2022), is associated with cardiorespiratory benefits (Chastin et al., 2019), therefore while guidelines for physical activity focus on moderate intensity, a growing bank of evidence suggests exercising at a lower intensity may still be of benefit (Chastin et al., 2019).

5.7 Conclusion

To conclude, the bespoke MVPA app more accurately measured relative moderate intensity compared to the native Apple Watch native activity app, when assessed against the criterion %VO_2R measure. Exercise guidelines and wearable devices like the Apple Watch should look to incorporate relative measures of physical activity in order to individualise physical activity monitoring and prescription more accurately, and with a concomitant move away from arbitrary absolute values that apply a single exercise goal to the mass population, such as 100 steps·min^{-1} walking cadence. Additionally, while relative intensity measures will never be accessible to everyone, the current study has found that subjective ratings have a high level of uncertainty when used to measure physical activity intensity. Moreover, the practical use of subjective ratings outside of controlled laboratory conditions is questionable.

Funding

The authors received no specific funding for this research.

6. The efficacy of metronome and haptic cues to guide walking intensity to criterion moderate intensity

6.1 Introduction

Walking is one of the most popular forms of physical activity in the UK, with 71% of the UK population walking at least once a week (Department for Transport, 2016). Walking is not only used as a form of physical activity, but is often used as a form of transportation, occupation, and in domestic duties completed throughout the day. Physical activity guidelines have been developed to encourage people to engage in moderate intensity to improve health outcomes (nhs.uk, 2022). The limitation with these guidelines is that they are subjective and can often be misinterpreted (Knox et al., 2013; Vaara et al., 2019; Piercy et al., 2020). Because of this, other more easily interpreted guidelines have been developed to reduce the subjective interpretation of guidelines. A walking cadence ≥ 100 steps·min^{-1} has been reported to sufficiently meet the demands of MPA (Tudor-Locke *et al*., 2018, Marshall *et al*., 2009, Nielsen *et al*., 2011, Abel *et al*., 2011) and authors have advocated for its use as a simplistic health message as a means of meeting absolute moderate intensity physical activity. However, more recent evidence suggests this absolute approach to exercise is potentially misleading a large percentage of the population with inaccurate exercise goals (Serrano et al., 2017; Abt et al., 2019).

Wearable devices have increased the opportunity for ‘self-quantification,’ which is the ability to track one’s movement and ‘upskill’ self-knowledge of activity and intensity while performing physical activity. Individualising exercise intensity in the general population, via physiological responses such as heart rate, are emerging in the literature and practice

(Almalki, Gray and Sanchez, 2015). The instantaneous accessibility of data available via wearable devices offers the opportunity for health professionals to individualise exercise and prescribe exercise goals more accurately. Currently on the Apple app store there are 41,517 healthcare apps available (Statista, 2022b). Apps have also been developed to encourage the tracking of movement and exercise using heart rate, GPS, and accelerometery, to encapsulate users with individualised data, thus allowing for more accurate exercise monitoring and prescription.

Wearable devices have also incorporated nudge theory, which proposes positive reinforcement and indirect suggestions as a method to influence behaviour and decision making (King et al., 2008). The Apple Watch, the highest selling wearable device worldwide (Statista, 2022a), has a number of these software developments to promote movement, such as hourly notifications to stand if one has been inactive and prompts to complete exercise to meet required exercise goals on a daily, weekly and monthly basis.

Nudge theory has also been incorporated into devices by several manufacturers to guide exercise intensity in real-time. For example, in the Garmin Forerunner, nudge theory is used to guide running pace, notifying the user if they are above, in line with, or below the required running speed to attain specific km splits. These nudges are given sporadically throughout exercise to guide the user to the correct running speed. This nudging concept to guide exercise intensity has also been implemented in walking, albeit using more simplistic methods, via cadence cueing. Participants walking speed is directed via an external metronome guiding the user to a particular walking cadence, synchronously, with relative success (Ducharme *et al.,*2018, Rowe *et al.,* 2012). For example, participants are instructed to synchronously take a step with each beat of the metronome, and this cadence is prescribed at different speeds, thus a metronome speed of 140 beats·min^{-1} should in theory, elicit a walking cadence approximate to 140 steps·min^{-1}.

The application of cadence cueing within wearable devices is a novel approach to exercise guidance. Wearables can continually monitor both the acute and chronic physiological responses to exercise and can continually adapt and modify exercise prescription i.e., acutely. Speeding up or slowing down the cadence cue could theoretically be administered depending on the level of exertion required. In the long term, and as health improvements are made, wearable devices could modify the exercise prescription based on improvements in cardiovascular health parameters such as resting heart rate, that wearable devices already measure. As resting heart rate decreases with improved cardiovascular health (Nystoriak and Bhatnagar, 2018), the intensity required to continue to meet relative moderate intensity would require adjustment. Without the wearable device this would require manual calculation and adjustments, however, wearable devices have the capacity to adjust this automatically without the user having to intervene.

Additionally, as the wearable device is in such proximity to the body and being in direct contact with the skin, it has unique opportunities to apply haptic, audio, and visual nudges to guide exercise intensity that have not been previously plausible through mobile devices. It is therefore important to understand how wearable technology could be used to apply cadence cueing during walking. Therefore, the main aim of this study was to investigate the application of metronome and haptic cadence cueing in guiding participants to walk to criterion moderate intensity, 40% HRR. A secondary aim was to examine how accurately participants could perform a self-paced walk when instructed to do so based on the NHS guidelines for moderate intensity (nhs.uk, 2022).

6.2 Methods

6.2.1 Study pre-registration

The study design, including a statistical analysis plan, was pre-registered prior to data collection, and can be found at https://osf.io/j39fa. STROBE guidelines were adhered to throughout the reporting of this observational study in line with guidelines (von Elm et al., 2007). A STROBE checklist can be found in the Appendix B.

6.2.2 Ethics

Institutional ethics approval was obtained from the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull (REF – FHS230) additional ethical considerations can be found in Chapter 3.

6.2.3 Study design

This was an experimental study, with participants attending the laboratory on one occasion. The visit was the final laboratory visit for participants, performed after the two visits discussed in Chapter 6.

6.2.4 Participants

74 participants who were recruited for the study in chapter 5, also completed this study. Participants were aged between 18-65 years of age (see Table 6.1 for demographic data) provided written informed consent and participated in the study. Participants were excluded from participation if: 1) they were classified as moderate or high-risk according to the ACSM risk classification criteria (Riebe, 2018), 2) they were unable to walk on a

motorised treadmill, 3) they had a BMI ≥ 35, 4) they were currently prescribed medication that altered the heart rate response to exercise (e.g., beta-blockers), or 5) they had an injury or disability that altered their gait pattern. Participants were recruited from the University and local community through written promotional material and personal communication.

6.2.6 Development of the Apple Watch ‘MVPA’ app

The app design and technical specification can be found in Chapter 3.

6.2.7 Setting

Participants were recruited from May 2021 for a 12-month period. All laboratory trials were completed on campus at the University of Hull.

6.2.8 Pre-trials

Prior to experimental trials has been described in Chapter 3.

6.2.9 Apple Watch Resting Heart Rate

The 7-day resting heart rate information can be found in Chapter 3.

6.2.10 Experimental trials

Participants completed three 10-minute overground laboratory walking trials on a ~60 m figure-of-8 track. Initially participants were instructed to complete a self-paced walking trial with the following instruction:

‘*You should aim to walk at a moderate intensity. The way the NHS describe moderate intensity is exercise that raises your heart rate, makes you breathe faster and feel warmer. One way to tell if you're working at a moderate intensity level is if you can still talk but not sing.’*

Participants were then randomly assigned to one of two conditions: metronome or haptic cues. Participants completed two additional trials in a randomised order, with the MVPA app (via Apple Watch) cueing cadence (see walking cadence in Chapter 3 for more detail) via metronome or haptic feedback. Participants were instructed to walk in time with the cadence cue. The first minute of activity was discarded for habituation, and the final minute for expectation effect. Participant’s heart rate and cadence were recorded throughout using the MVPA app. Walking trials were video recorded via an Apple iPhone XS positioned at the end of the figure-of-8 track to analyse cadence in line with best practice (Johnston *et al.,* 2020). For each minute cadence was independently counted by the lead investigator from the video footage, as well as being recorded via the Apple Watch MVPA app. Supplementary analysis of 30 randomly selected participants was conducted to investigate cadence synchronisation with the metronome beat, with one minute from each randomly selected participant randomly selected for additional analysis to identify cadence and metronome synchronisation. Participants were granted a 10-minute break between trials to reduce any impact of training or habituation before completing the final trial.

6.3 Statistical analysis

6.3.1 Statistical models

A posterior distribution of mean walking cadence over a 10-minute period was compared to the posterior distribution of walking cadence set by the Apple Watch to align with 40% HRR for metronome and haptic cues. The 40% HRR measured by the Apple Watch was considered the response variable. To do this, another series of Bayesian regression models were fitted (see models fitted subsection below). These models were compared to determine the best model in terms of out-of-sample prediction accuracy and data fit (see comparison methods subsection below). The posterior distribution of the differences between measured and estimated walking cadence was used to compare the difference between walking cadence and cadence cue for both the haptic and metronome cue. Further sub-analysis of 30 participants was completed on one-minute of each participant's cadence to estimate how accurately individuals were able to synchronise with the beat of the metronome cue, by estimating a posterior distribution of differences between the metronome and participants' cadence. A region of practical equivalence (ROPE) that ranged from -0.1 to 0.1 seconds was used, which for practical purposes was considered equivalent to a zero difference. Descriptive statistics highlighted the accuracy of each foot contact against the metronome cue.

6.3.2 Models fitted

The models estimating MVPA (40% HRR) were fitted with different response distributions (Gaussian, Skew Normal, and Student's t-distribution) and different prior distributions: 1) general weakly informative prior, 2) a measurement constrained prior that distributes probability over possible values constrained by the particular measurement, and 3) strongly informative priors, informed by previous studies. Each of these models included: 1) fixed effect models, 2) random intercept models, where intercepts for each individual measure was allowed to vary; and 3) models, where both intercepts and slopes for each individual were allowed to vary. This provided a pool of models for each analysis which were compared (see comparison methods subsection below). The basic structure of the fixed effects, random intercept and random slope models are detailed below, these were adjusted to accommodate the different response distributions and priors outlined above. Fixed effects model $y_i \sim Normal(\mu_i, \sigma_e)$ $\mu_i = \alpha + \beta x_i$ Random intercept model $y_i \sim Normal(\mu_i, \sigma_e)$ $\mu_i = \alpha_{j[i]} + \beta x_i$ $\alpha_j \sim Normal(\alpha, \sigma_\alpha)$ Random intercept and slope model $y_i \sim Normal(\mu_i, \sigma_e)$ $\mu_i = \alpha_{j[i]} + \beta_{j[i]} x_i$ $\alpha_j \sim Normal(\alpha, \sigma_\alpha)$ $\beta_j \sim Normal(\beta, \sigma_\beta)$. In these models $\alpha_{j[i]}$ indicates that each participant is given a unique intercept, issued from a Normal/Gaussian distribution, centred on α, the grand intercept, meaning that the model allowed for different mean values for each participant. The varying slopes were assigned a prior distribution centred on the grand slope β, and with standard deviation σ_β. X represents a categorical variable which includes the various methods of measurement to be compared. Given that the predictor categories are from rating scales, they should not be assumed equidistant with respect to their relationship to the response variable, the distance between adjacent predictor categories are estimated from the data and may vary across categories.

6.3.3 Comparison methods

All the models produced were compared using three methods in the following order of priority: Leave-One-Out cross-validation (LOO), Bayes Factor, Bayesian R^2. Firstly, LOO information criterion (LOOIC) was used to determine the relative predictive performance of the models in terms of pointwise out-of-sample prediction accuracy using log-likelihoods from posterior simulations of parameter values (Vehtari, Gelman and Gabry, 2017). A model was considered better if it produced a LOOIC difference greater than twice its corresponding standard error. Where a comparison of models using LOOIC does not achieve this level of difference, the second model comparison method was used where Bayes Factors (BF) quantified the support for one model over another. Where a particular model achieved a BF_{10} greater than 10, relative to other models, it was considered the better model. To determine which model was better using LOOIC and then BF, the model with the highest Bayesian R^2 was selected. The Bayesian R^2 is seen as a data-based estimate of the proportion of variance explained for new data (Gelman et al., 2019).

6.4 Results

Seventy-seven participants were initially recruited and examined for eligibility. All participants were eligible to take part in the study and were initially included. Seventy-four participants (3 non-participation) completed all trials and were included in the study (Table 6.1). Reasons for non-completion were lack of time (2) and family bereavement (1).

Table 6.1 Mean (SD) participants demographic data.

	Sex	**Age (years)**	**Body mass (kg)**	**Stature (cm)**	**BMI (kg·m^2)**	**Leg Length (cm)**
Mean (SD)	43% F	30.7 (10.3)	74.06 (14.8)	172.7 (10.1)	24.8 (4.4)	89.2 (6.2)

The mean (SD) for walking cadence, from the Apple Watch and video analysis, mean %HRR, and percentage of participants completing trials in the criterion 40% - 59% HRR moderate intensity and within the ROPE (37.5 – 59% HRR) in all three trials is presented below in Table 6.2.

Table 6.2 Means (SD) walking cadence as recorded via the Apple Watch and the Video recording, mean cadence cue prescribed via a metronome or haptic feedback, the mean %HRR, and percentage of participants who maintained a mean %HRR on or above 40% HRR.

Trial	**Mean watch walking cadence (SD)**	**Mean video walking cadence (SD)**	**Mean cadence cue (SD)**	**Mean %HRR (SD)**	**Percent of participants completing trials with a mean %HRR ≥ 40 - 59**	**Percent of participants completing trials with a mean %HRR within the ROPE ≥ 37.5 - 59**
Self-paced trial	127 (9)	127 (9)		42 (3)	41%	50%
Metronome cue	125 (19)	127 (12)	139 (14)	44 (7)	76%	81%
Haptic cue	124 (10)	124 (11)	138 (16)	43 (8)	65%	68%

Figure 6.1 illustrates the posterior distributions for %HRR from the three overground walking trials. Specifically, the mean effect (ME) and 95% credible intervals (CI) for each posterior distribution were, self-paced ME: 41% HRR CI: 39% to 44% HRR, metronome cue ME: 45%CI: 42% to 47% HRR, haptic cue ME: 43% HRR CI: 41% to 45% HRR.

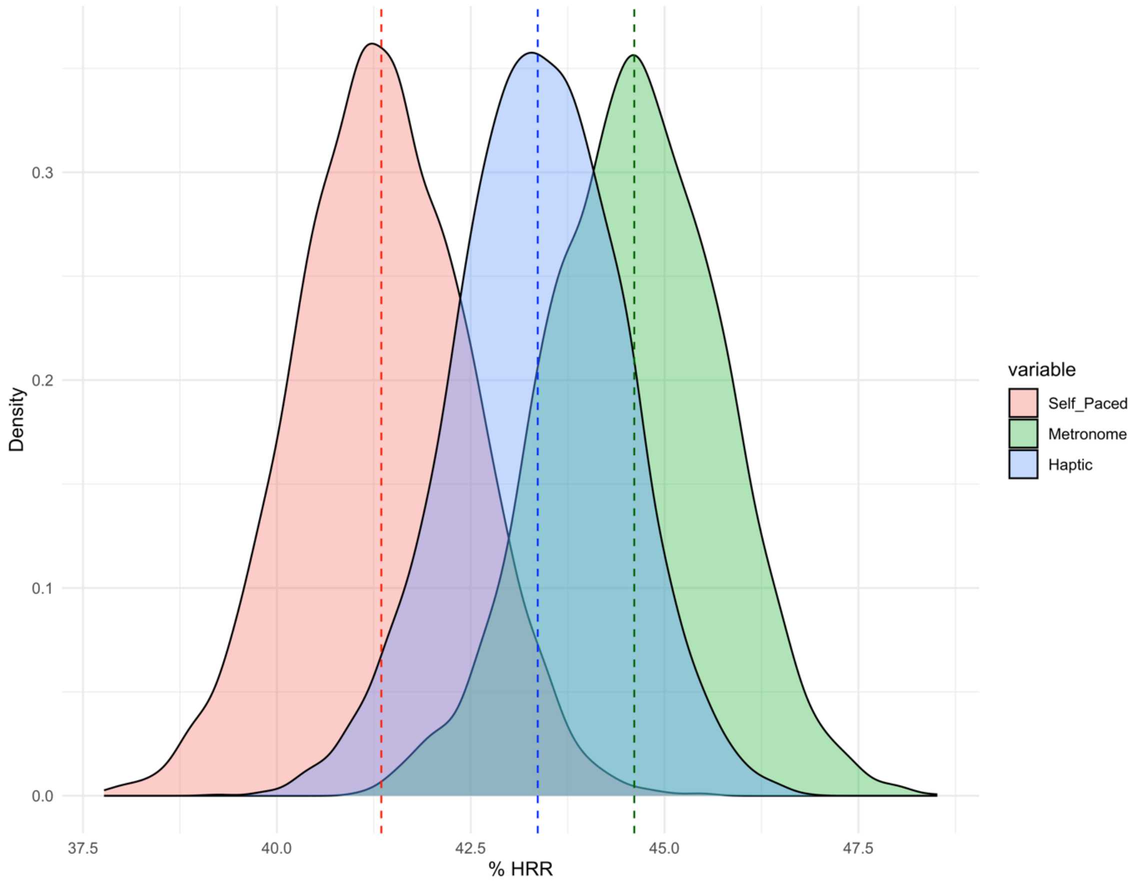

Figure 6.1 Posterior distributions for %HRR during the metronome, haptic cue, and self-paced walking trials.

Figure 6.2 illustrates the posterior distributions for the metronome trial, including the mean walking cadence recorded via the watch (steps·min^{-1}), the mean walking cadence recorded via the video analysis (steps·min^{-1}), and the mean metronome cue administered (beats·min^{-1}). Specifically, the mean effect (ME) and 95% credible intervals (CI) for each posterior distribution were, walking cadence from the Watch ME: 124 CI: 121 to 127 steps·min^{-1}, walking cadence from the video analysis ME: 126 CI: 124 to 129 steps·min^{-1}, and the metronome cue ME: 138 CI: 136 to 140 beats·min^{-1}.

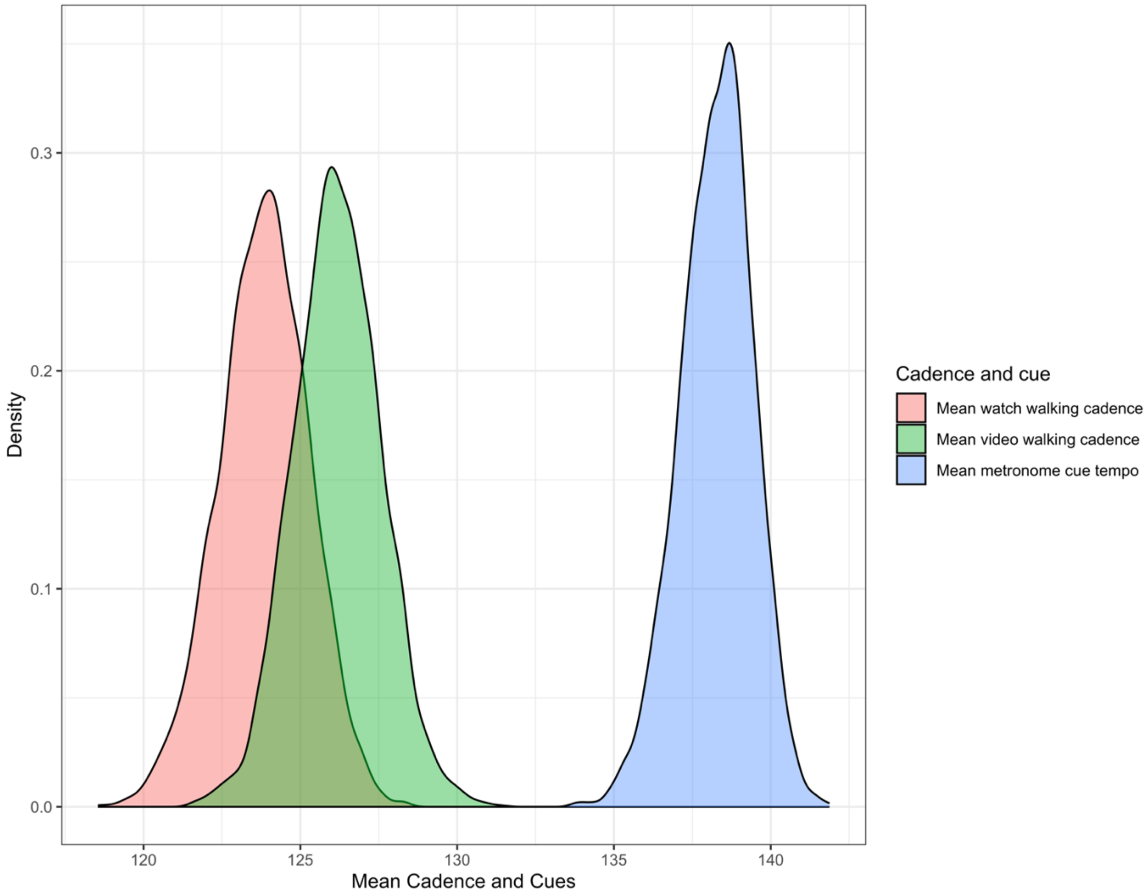

Figure 6.2 Posterior distributions for the measurement of walking cadence during the metronome trials for mean watch walking cadence, mean video analysis walking cadence and mean metronome tempo.

Figure 6.3 illustrates the posterior distributions for the haptic cue trial, including the mean walking cadence recorded via the Watch (steps·min^{-1}), the mean walking cadence recorded via the video analysis (steps·min^{-1}), and the mean haptic cue administered (beats·min^{-1}). Specifically, the mean effect (ME) and 95% credible intervals (CI) for each posterior distribution were, walking cadence from the Watch ME: 122 CI: 120 to 125 steps·min^{-1}, walking cadence from the video analysis ME: 122 CI: 120 to 125 steps·min^{-1} and the haptic cue ME: 140 CI: 137 to 143 beats·min^{-1}.

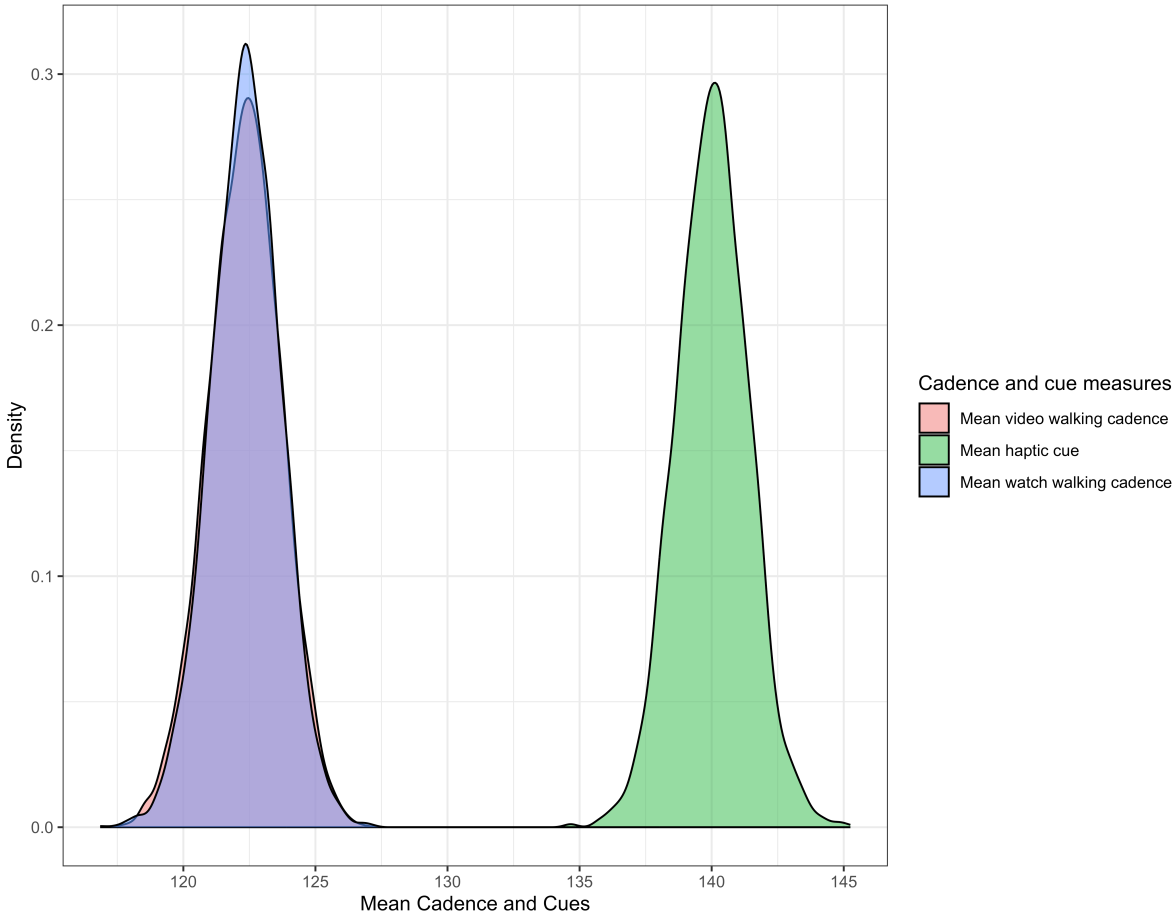

Figure 6.3 Posterior distributions for the measurement of walking cadence during the haptic cue trials, for mean watch walking cadence, mean video analysis walking cadence and the mean haptic cue tempo.

Figure 6.4 illustrates the posterior distributions for the metronome and haptic cue trials, including the mean walking cadence recorded via the video analysis (steps·min^{-1}) for both the metronome and haptic cue trials, and the mean metronome and haptic cue administered (beats·min^{-1}). Specifically the mean effect (ME) and 95% credible intervals (CI) for each posterior distribution were, walking cadence from the video analysis for the metronome cue trial ME: 126 CI: 124 to 129 steps·min^{-1}, the metronome cue administered

ME: 138 CI: 136 to 140 beats·min^{-1}, the walking cadence from the video analysis during the haptic cue trial 122 CI: 120 to 125 steps·min^{-1} and the haptic cue administered ME: 136 CI: 134 to 139 beats·min^{-1}.

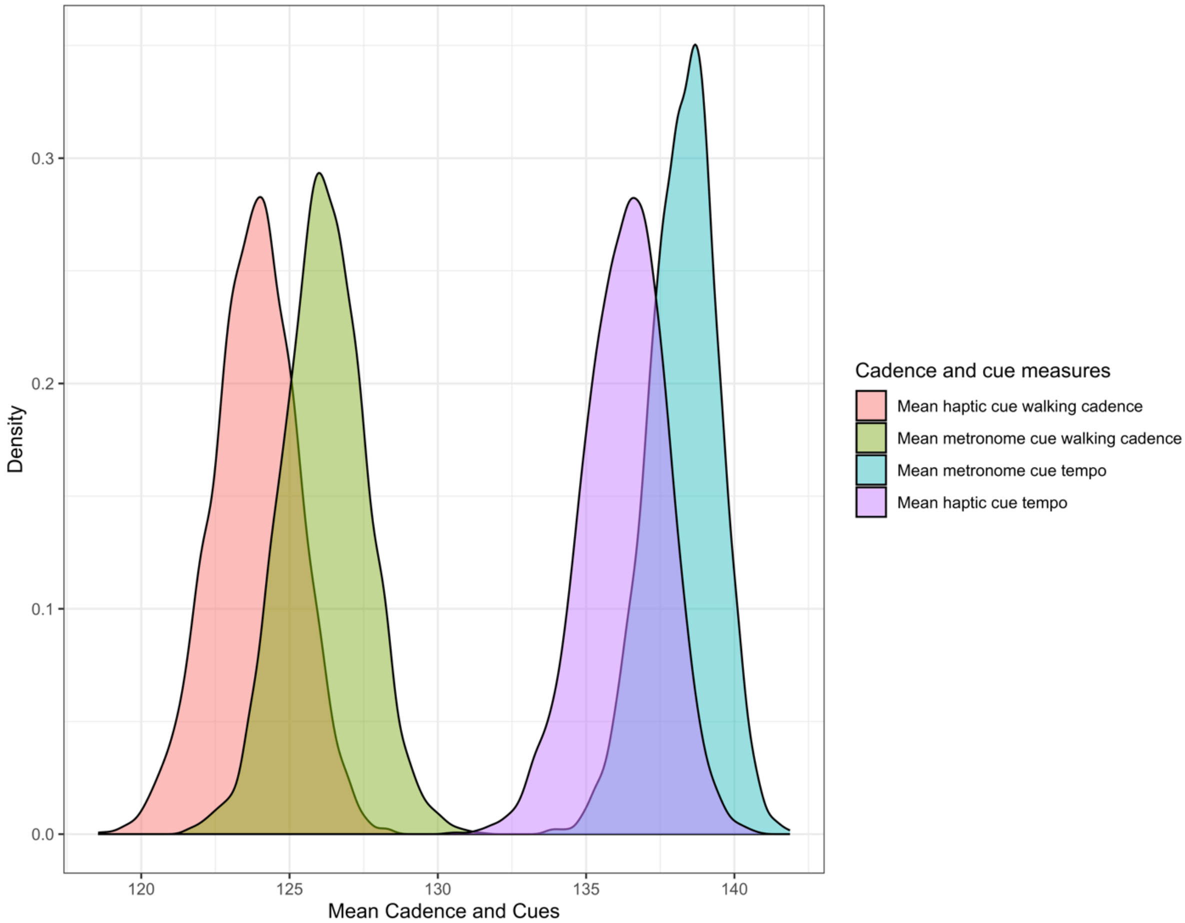

Figure 6.4 A comparison of posterior distributions for the walking cadence trials during the metronome and haptic cadence cue.

Analysis from the subsample of 30 participants where synchronisation of walking cadence with metronome cue was analysed for 1 minute of walking, showed that 43% of all steps were synchronised within the ROPE.

Figure 6.5 illustrates the posterior distribution for the mean time between metronome cue and foot contact in the subsample of 30 participants. Specifically, the mean effect (95% CI) was ME: -0.92 CI: -1.81 to -0.04 s.

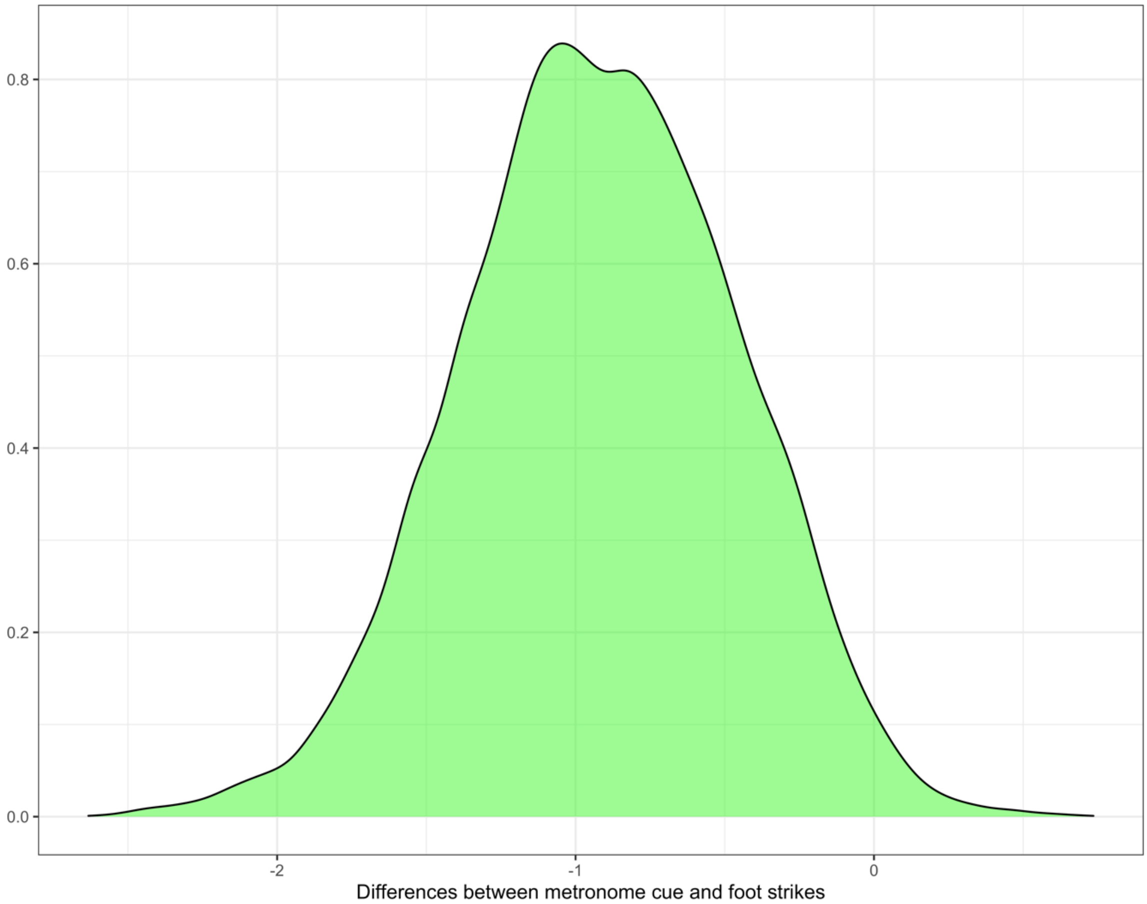

Figure 6.5 Posterior distribution for the mean difference (s) between consecutive metronome cues and foot contact

Figure 6.6 illustrates the posterior distribution for the mean time between consectuvie foot contacts in the subsample of 30 participants. Specficially, the mean effect (95% CI) was ME:

0.378 CI: 0.31 to 0.46 s.

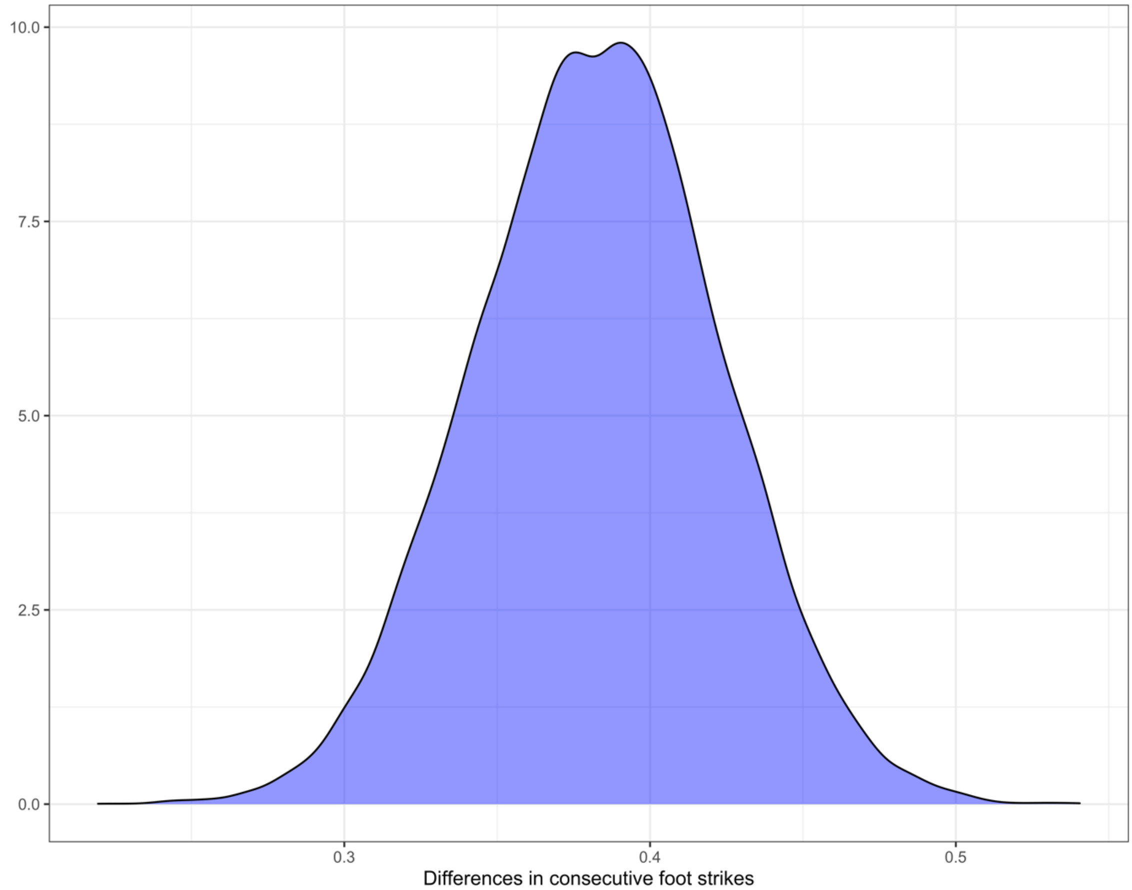

Figure 6.6 A posterior distribution for the mean difference (in secs) between consecutive foot contacts.

There was no deviation from the pre-registration reported but one additional analysis conducted. A Bayesian posterior distribution was created to model the mean time taken between consecutive foot contacts.

6.5 Discussion

6.5.1 Guidance to criterion moderate intensity

The main findings from this study are that it may be better to use a metronome or haptic cue rather than government guidelines to help people achieve criterion moderate intensity, 40% HRR. While all walking trials had a mean effect above the 40% HRR threshold (see Figure 6.1), the metronome and haptic cues both guided a greater proportion of users to moderate intensity (76% and 65%, respectively), compared to self-paced walking guided by NHS moderate intensity guidelines (41%). When the ROPE (37.5% HRR or higher) is taken into consideration similar trends exist, with 81%, 68% and 50% of participants exercising at moderate intensity or above during the metronome, haptic cue, and self-paced trials, respectively. Using a metronome or haptic cue to guide exercise intensity is a novel approach, and to the authors' knowledge the first of its kind. Moreover, the MVPA app used an adjustable and responsive cue, such that the cadence cue had the capacity to change during walking trials depending on the participants heart rate response. If the participant's heart rate was not at the criterion 40% HRR then the cadence cue would increase. Likewise, if the participant's heart rate was above the threshold set at 45% HRR, then the cadence cue would slow down. The cadence cue was designed like this to ensure that participants were performing physical activity at the minumum required intensity to reach relative-intensity MPA.

6.5.2 Metronome cadence cueing

While using a metronome to guide walking cadence in healthy populations has previously been used with relative success (Wittwer, Webster and Hill, 2013; Ducharme et al., 2018), the findings from this study indicate that participants, on the whole, were unable to match their walking cadence to the metronome cue with accuracy. Participants' mean (SD) walking cadence during the metronome cue trials was 125 (19) while the mean metronome cue was administered at 139 (14), identifying over 10% error in the guided walking cadence and actual walking cadence as measured by the Watch. While this study contradicts previous findings, the differences in methodology may explain why these findings contrast. In the trials performed in previous studies, cadence cues were set at a given speed for the entire trial. For example, Ducharme *et al.* (2018) instructed participants to walk over a pathway between two cones placed 13 m apart. Authors used a GAITRite mat electronic walkway system that was 7 m in length placed in the middle of a 13 m walkway that alllowed for collection of temporal and spatial information about each footstrike. Participants performed 12 crossings in total at 7 randomly assigned metronome speeds: 80, 90, 100, 110, 120, 130 and 140 beats·min^{-1}. Results indicated that participants were able to meet the required walking cadence with relative accuracy at all metronome speeds (beats·min^{-1}). At the fastest metronome speed administered (140 beats·min^{-1}) participants had a mean cadence of 138.6 (1.1) steps·min^{-1} with a mean absolute percentage error (SD) of 1.0% (1.4). Similarly Wittwer, Webster and Hill (2013) used a GAITRite electronic walkway in a comparable study design, but with older participants. Initially, participants mean cadence was recorded from two baseline walking trials across a 12.3 m walkway with the GAITRite mat placed in the middle, from which cadence was recorded and a metronome set to replicate that speed. Participants then performed the same walking trials with the metronome cue, initially synchronising their cadence to the metronome by walking on the spot, before performing one single 12 m walk. Results indicated that participants were able to cue their walking cadence with the metronome cue, with mean cadence cue (SD) being 115.4 (8.8) beats·min^{-1} while mean cadence during metronome trials was 116.5 (9.2) steps·min^{-1}, and cadence variablity was reported at 3.21 (0.7)%.

While both studies identified participants' ability to align walking cadence with an external metronome, the descrepancies in study design between these previous studies and the current may highlight the reduced capability to cadence cue to a metronome accurately in the current study. In the current study participants performed 10-minute trials on a figure-of-8 track, which may more closely align to walking in a real world setting whereby pedestrians do not walk in straight lines but have to negotiate corners (Franěk, 2013). The ability to maintain a cadence that matches a metoronome cue may be hindered by the variable stride length undertaken when cornering, where often a reduced stride length occurs in one or both legs when walking around a corner, which would impact one's ability to synchronise with the metronome cue (Bland et al., 2019). Additionally, both studies incorporating the GAITRite pathway (Wittwer, Webster and Hill, 2013; Ducharme et al., 2018) performed trials lasting significantly less time then the trials performed in the current study. As the trials were 10-minutes in duration, attentional focus may have impacted participants ability to allocate mental resources to an external stimuli continually without distraction. Attentional focus in the context of exercise performance refers to the process in which a person allocates the mental resources to cues, stimuli, or states (Neumann, 2019). Attentional focus can be split into internal i.e., attending cognitive, emotional, and pain cues or external i.e., environmental cues (APA Dictionary of Psychology, 2023). As the participants in this study performed three, 10-minute trials focussing attention on an external stimulus, complete focus may have been difficult to sustain for the duration. Nobre, Nobre and Coull

(2010) refer to sustaining monotonous, intellectually unchallenging tasks as vigilant attention. We often sustain this level of efficient conscious stimulus processing to detect stimuli including simple cognitive or motor tasks that do not require higher levels of attention. Cueing walking cadence to an external metronome played continually could be deemed as a vigilant attention task, as participants attention is not triggered by novelty. Vigilant attention operates on a short cycle refresh system, that has been estimated to refresh approximately every 10 seconds (Langner and Eickhoff, 2013). This may be one reason participants were unable to maintain the required walking cadence for the duration of the trial. While laboratory conditions were implemented, other external conditions such as the laboratory space around them and internal attending cognitive distractions, such as thoughts about daily tasks, work, or evening plans may have disturbed the mental resources required to maintain walking cadence to the metronome beat for a sustained period, impacting participants ability to accurately cue cadence to a metronome continually. A theme that arose from the semi-structured interviews in Chapter 7 was escapism when walking, participants often referred to thinking about their daily tasks, work commitements or the environment around them when walking, which may have impacted the laboratry trials.

Another reason there could be discrepancies between previous research findings and the current study is the novel approach taken in modifying the metronome cue during trials, depending on %HRR. As previously stated, if a participant’s %HRR was below the minimum criterion threshold for moderate intensity, the metronome cue tempo would increase. While this novel approach had the capacity to guide 81% of participants to criterion moderate intensity or above, the variance in metronome tempo may have impacted participants ability to match the cadence cue as it was not a stable or fixed variable. While the difference between metronome cue and walking cadence (metronome cue 139 (14) beats·min^{-1} and walking cadence 125 (19) steps·min^{-1}) seems a sizeable difference between metronome cue and walking cadence, in real terms the difference in timings between each metronome cue at 125 beats·min^{-1} and 139 beats·min^{-1} is 0.48 s and 0.432 s respectively, which is a difference of 0.048 s. As the relationship between cadence and metronome cue is non-linear, a small change in metronome tempo can have a large effect on cadence over the course of a minute. Authors have tried to determine the threshold for detecting tempo change in both music and metronomes (Ellis, 1991; Mcauley, 2010; Patel and Iversen, 2014). Ellis (1991) investigated the threshold for detecting tempo change in highly musically experienced and low muscially experienced participants. Results indicated that those with less musical experience were able to detect lower percentage changes in tempo, and for both groups of participants detection was more noticeable during decreases in tempo, and at slower speeds. At the mean metronome speed in this study (139 beats·min^{-1}), according to Ellis (1991) the mean detectable percentage change increase would be approximately 6-7% for high and low muscially experienced participants. In this study, that equates to a detectable change of approximately 8-10 beats·min^{-1}. Likewise, for a detectable change in decreasing tempo at the approximate mean metronome speed from this study (139) results were very similar with 6-7% detectable change reported by Ellis (1991). The MVPA app's capabilities meant that the metronome speed was able to regularly change within this minimal 6-7% detectable change, which may have gone unnoticed to the participant.

The change in metronome tempo may also have caused disruption to participants' capabilities in predicting the metronome tempo. Patel and Iversen (2014) hypothesised that beat perception is a complex brain function involving precise communication between auditory regions and motor planning regions in the cortex. These authors believe the simulation of periodic movement in motor planning regions provides a neural signal that enables the auditory system to predict the timing of upcoming beats, such that in the context of this study the response is not to the metronome cue, but movement is generated to predict when the foot contact should occur based on the repetitive nature of the stimuli. These authors referred to this phenomena as 'action simulation for auditory prediction.' This may give suitable reason as to why participants were unable to accurately align their walking cadence to the metronome cue in the current study, as when the metronome changed tempo, participants' ability to realign walking cadence may have been hindered by this predictvie mechanism. When we consider humans inability to hear tempo change below 6 - 7% (Ellis, 1991), and the motor planning regions predictive capacity to create human movement based on predicting a re-occuring stimuli, one's ability to change walking cadence to align with an adjusting metronome tempo may not be immediately acheivable, and may explain why in the current study participants were unable to match their walking cadence with a metronome cue.

6.5.3 Haptic cadence cueing

The haptic cue was less effective at guiding participants to MPA when compared to the metronome cue, but slightly more effective then government guideline instruction. To the best of the authors knowledge this is the first study of its kind whereby participants walking speed has been guided via a haptic cadence cue in healthy populations for a sustained period of time, and the capacity to change haptic cue tempo depending on participants' exercise intensity. The results suggest there may be scope for haptic cadence cues to be a useable tool for guiding walking intensity to criterion 40% HRR.

Previous research (although not directly comparable) has attempted to use haptic cues as a means of directing walking speed and cadence. Ling *et al.* (2022) investigated the use of a vibrotactile (relates to a device that is able to administer a vibration through touch) cueing device attached around the waist in stroke patients. Vibrating mechanisms were deployed on the bilateral sides of a pelivc belt, where each vibration cue directed participants to step forward. When the vibration was on the left and right side of their waist, participants were instructed to step forward with the corresponding leg. Participants performed 8 trials in total on a 10 m walkway. In the experimental group participants performed 2 pre-test walking trials at preferred walking speeds, 4 training trials using the cadence device, and 2 post-test trials again without the cue at their preferred walking speed. The control group performed pre, training, and post-walking trials in a similar fashion to the experimental group, but were instructed to 'walk as fast as possible' in the training trials, and no cadence cues were administered. Participants in the experimental walking trials increased walking speed by approximately 23% and had an increased walking cadence during the training trials and post-test trials compared to baseline. While the study's findings are relevent to the application of a haptic cadence cue to guide walking, the authors did not report participant sycnhronisation with the cadence cue, or whether participants were able to match their walking speed with the speed of the cadence cue. Additionally, participants were post-stroke and only 4 participants were assigned to each condition.

Other authors have investgiated peoples' ability to feel haptic vibration change. Lylykangas *et al.* (2013) investigated the use of a vibrotactile cue on the wrist and waist to examine if participants could correctly identify changes in vibrotactile tempo. Results indicated that the speed regulation stimuli were detectable for all three vibration speeds, with participants' ability to detect change ranging from 77-100%. It is worth noting that participants in this study did not perform walking trials, but instead participants were placed in front of a screen and told to respond to the changing stimuli via response buttons. In the trial a 'next stimulus' text would appear on screen for 1500 ms, followed by a fixation point on screen for 1500 ms and finally a blank screen for 500 ms before the stimulus was changed. Participants then pushed a button for increase, same tempo, or decrease in vibration tempo. While this study highlights peoples' ability to percieve vibrotactile cue changes, its applicability to walking is questionable. Specifically, attentional focus may not be on the vibrotactile cue, the arm swing movement may reduce vibration strength from the wrist haptic cue, and participants are not pre-empted about changes in vibration speed. Other authors have sought to investigate one's ability to synchronise walking speed with periodic vibrotactile guidance. Karuei and MacLean (2014) invesitgated the use of haptic notifiers placed on participants wrist as a method of guiding walking cadence. Each trial consisted of 20 s walking guided via the vibrotactile guidance and 40 s without. Participants performed 16 trials in total, with three trials of five differing guidance speeds, and one dummy run. Guidance rates were coordinated individually to each participant's fastest and slowest cadence speeds. Results indicated that cadence cues affected participants walking cadence when conciously followed, less than 5% deviation was observed in four out of five cue rates, and the fastest cue rate produced less then 10% deviation. While these results indicate participants were able to somewhat synchronise their walking cadence with the haptic cue, it is easier to maintain focus on an external cue for short periods of time (Langner and Eickhoff, 2013). Applying this over a sustained period of time, which is more likely to replicate walking in a real world setting, is likely to see greater deviation from the haptic guidance. Participants in the study by Karuei and MacLean (2014) had a mean walking cadence of 124 steps·min^{-1}, and the mean haptic cue guidance was 138 beats·min^{-1} with a mean percentage error of 10.1%. Karuei and MacLean (2014) did not report the mean walking cadence or vibrotactile tempo, never-the-less the results are somewhat comparable to the current study, and suggest that it may be difficult to accurately synchronise walking cadence with a haptic cue, at least for sustained periods.

6.5.4 Metronome cue synchronisation

Participants capability to align their walking cadence with a metronome cue relies on a persons ability to synchronise each step accurately with the metronome tick. There is evidence to suggest that the synchronisation process is an autonomous process and derived from the interaction between the motor and auditory systems processed on a peripheral level in the spinal chord (Molinari et al., 2003), similar to the process described above (Patel and Iversen, 2014). Authors have previously investigated peoples' ability to synchronise walking cadence with a metronome cue. Dickstein and Plax (2012) examined walking to metronome cues at 60, 110, and 150 beats·min^{-1} over an 8 m walkway with pressure sensitive footswitches placed under the foot. Participants' ability to synchronise their walking cadence with the metronome cue was examined. Results indicated that the highest rate of synchronisation occurred at 60 beats·min^{-1}, with an intraclass correlation of 0.9 for left foot contact and 0.89 for right foot contact. At 110 beats·min^{-1} the intraclass correlation was moderate (0.68 and 0.75 for left and right foot, respectively). At the fastest metronome cue administered (150 beats·min^{-1}), synchronisation was poor with an intraclass correlation of 0.41 and 0.37 for left and right foot, respectively. These results are comparable to the findings in the current study which indicated, from the 30 participants, one minute analysis of metronome cue and cadence synchonisation, that only 43% of foot contacts were synchronised (whereby foot strike occurred within 0.1 seconds either side of any metronome cue) with the metronome cadence cue. There may be a number of factors that have impeded participants' ability to synchronise their walking cadence within the current study. As previously discussed, participants' stride length shortening while cornering may have altered stride rate (Bland et al., 2019) which could have caused participants walking cadence to be asynchronous with the metronome cue, as they completed turns at the top and bottom of the figure-of-8 walking track. Additionally, one's ability to maintain attentional focus for a sustained period during the trials (Langner and Eickhoff, 2013) may have also impacted synchronisation, where maintaining concentration to a metronome cue for 10-minutes is difficult. As previously discussed, the changing of the metronome tempo may also have impacted participants' ability to sycnhronise their walking cadence accurately to the metronome cue. Pouliot and Grondin (2005) investigated peoples' sensitivity to auditory changes in music and a metronome. The initial tempo was set at 100 beats·min^{-1}. Changes in tempo were abrupt and ranged from 1% to 5% from the initial tempo with 1% incremental changes. In total there were 10 gradual variations, five accelerations, and five decelerations for both music and metronome conditions. The mean response time to ± 5% and ± 1% metronome tempo change were 1.33 – 3.67 s respectively, in the metronome condition. While participants had normal audition, their musical experience is unknown. Never-the-less, the results may explain why in the current study the rate of metronome synchronisation was poor. When we consider the highest mean rate of metronome tempo change took 1.33 s to be detected in the Pouliot and Grondin (2005) study, when put into perspective in the current study, at the mean metronome rate of 139 beats·min^{-1}, a rate of metronome cue being administered every 0.432 s, by the time a participant has detected the change in tempo, 3 metronome cues have been administered. At the slower tempo change and a mean response rate of 3.67 s, hypothetically, eight metronome cues would have been administered in this time. It is likely that all metronome cues within that period would be unsynchronised with walking cadence. While the magnitude of tempo change in this study was not standardised, nor was the rate of change, the instantaneous nature of the metronome changing tempo is likely to cause similar, if not greater delays in response time, and thus may explain why a high percentage of walking cadence is asynchronous to the metronome cue.

6.6 Study limitations

As this study took a novel approach to guiding walking cadence it is inevitable that there are some limitations that need to be considered. First, the MVPA app's capabilities to administer a strong haptic cue were limited by the Apple Watch haptic engine. There is a trade off between sleekness of design and having an engine within the device that can administer an adequately strong haptic cue. While the Apple Watch haptic engine administers cues for notifications, the strength and type of haptic cues are designed with this in mind, not providing walking cadence guidance. However, when used in an exercising environment with an arm swing associated with normal walking gait, a number of participants complained that they could not feel the haptic cue during trials, which will have impacted participants ability to sycnhronise walking cadence with the haptic cue.

Second, the Watch's capacity to modify cadence cue dependent on heart rate was designed to increase the cue tempo if heart rate was not above the 40% HRR threshold for moderate intensity. However, an oversight in its design meant that if a participant's %HRR was within the 40 – 45% threshold, and for example, the cadence cue was administering a metronome or haptic cue at a rate of 150 beats·min^{-1}, but the participants walking cadence was below this tempo e.g., 120 beats·min^{-1}, the app did not recognise this and reduce the cadence cue tempo to match walking cadence, but would continue to administer the cadence cue at the same rate. While this had no impact on guiding the participant to 40% HRR, it did impact participants' ability to sycnhronise to the cadence cue.

A further limitation within the study design may have been the self-paced walking condition with NHS instruction to walk at moderate intensity based on intrinsic feeling. While the results are still of interest, an additional baseline walking trial where participants were given no instruction prior to performing 10-minutes of walking, or told to walk at their normal walking speed, may have given greater insight into how participants' walk during daily ambulation, as well as giving greater insight into the MVPA app's and NHS guidelines ability to guide moderate intensity physical activity compared to a normal walking speed. There was a tendency from some participants in this study to walk as fast as possible when instructed to walk at moderate intensity or were unable to quantify the speed required to elicit the intrinsic feeling of moderate intensity from bodily markers such as warmth, heart rate, and breathlessness or one's abilty to talk but not sing. Previous findings suggest people tend to exercise more vigorously when instructed to walk at a moderate intensity to ensure they are performing physical activity adequately, rather then being able to guage moderate intensity accurately (Braham, Rosenberg and Begley, 2012).

6.7 Future direction

There is some evidence that cadence cueing has the ability to direct walking speed to MPA, but based on the findings of this study cadence cueing might not be fundamentally better at the current time compared to NHS moderate intensity guidelines. Future investigations should focus on a number of key areas including reducing the bias created in instructing participants to walk at moderate intensity. Participants do not necessarily understand the moderate intensity guidelines, but walk at an intensity that is faster than their normal walking speed to accommodate these instructions. Second, improving the strength of haptic feedback may offer the best training device in terms of real-world application and useability to wearable device users. It is unlikely that users would be willing to listen to a metronome cue to guide their walking cadence for any length of time in a real world setting. However, the haptic cadence cue is far less intrusive to the user, and could be used as a training mechanism to better guide users to a walking cadence that will elicit moderate intensity. The application of stronger haptics may not be currently possible with the Apple Watch, however, other devices are available that produce stronger haptic vibrations. Testing their applicability in guiding walking cadence via haptic feedback is warranted. Third, the metronome cue may not be plausible as a training device due to the monotonous tone that some participants found irritating. However, a more realistic approach could be to use music tempo to guide walking cadence. Investigating the ability of music to guide walking cadence and subsequently physical activity intensity in a similar fashion as the current study, for sustained periods and with replicable infastructure such as corrnering, is worth considering as this may encourage more people to use it. Additionally, the metronome cue offered the best results for guiding particiapnts to criterion moderate intensity, so using it as a training tool that can be turned on and off may help people to walk at the required speed.

Investigating shorts periods of exposure to metronome cues followed by non-guided walking would increase its useability.

Finally what is evident from the findings of the current study in comparison to previous cadence cue studies is that the duration of trials may have an impact on participants' ability to sustain sycnhronisation between walking cadence and a cadence cue. Its applicability therefore, in a realworld setting away from the laboratory is warranted, where pedestrians have to negotiate infastructure such as roads, other pedestrians, street infastructure, and cars. While synchronisation may not be applicable in this setting, ensuring people can accumulate exercise that induces cardiorespiratory benefit in daily living is important, and therefore using cadence cues as a training tool that can be turned on and off during daily ambulation may improve physival activity outcomes in the general public, and this warrants further investgiation.

6.8 Conclusion

To conclude, the cadence cues (specifically the metronome cue) guided more users to criterion moderate intensity (40% HRR) compared to NHS guided self-paced walking. Apple and other wearable device manufacturers may wish to incorporate such tools into their devices in order to offer better guidance in reaching moderate intensity. Additionally, while wearable devices are not accessible to everyone, the current study has found that NHS guidelines for moderate intensity may serve some use in guiding users to moderate intensity physical activity, but the subjective nature of the guidelines means that often they can be difficult to interpret accurately.

Funding

The authors received no specific funding for this research.

7. Awareness and understanding of National Health Service physical activity recommendations: How do people interpret physical activity guidelines?

7.1 Introduction

Public health guidelines have been published by international governing bodies in a bid to increase physical activity participation across the population for many decades (Bull et al., 2020; Brown et al., 2022; nhs.uk, 2022; Thomas et al., 2022). Current UK physical activity guidelines suggest for adults, a minimum of 150 minutes of moderate intensity physical activity or 75 minutes of vigorous intensity physical activity should be completed on a weekly basis as well as two resistance training sessions. Data derived from the self-reported Active Lives Survey (Sport England, 2020) indicate that 61% of the UK adult population are classed as being active (completing 150 minutes of moderate intensity physical activity a week). However, this may be an over-estimate as it has previously been reported that large discrepancies between subjectively- and objectively measured physical activity exist (Colley *et al.,* 2018). A recent systematic review (Prince *et al.,* 2020) concluded subjective measures of activity underestimated sedentary time by 1.74 hours a day, while 72% of participants under-reported sedentary time compared to objectively, device-measured sedentary time. Additionally, Colley et al. (2018) compared self-reported and accelerometer-measured physical activity in 2,372 Canadian adults aged 18 – 79 years old, as part of the Canadian Health Measures Survey, reporting that, on average, Canadian adults reported more physical activity than that accumulated on an accelerometer. Adults reported completing 49 minutes of physical activity a day compared to 23 minutes a day recorded via an accelerometer. These findings are concerning but could be even more meaningful when we consider the discrepancies that exist in using absolute intensity, accelerometer cut points (METS), compared to relative physical activity intensity thresholds reported in Chapter 4. When we consider that absolute intensity thresholds tend to overestimate physical activity compared to relatively measured physical activity intensity (Abt et al., 2019), the likelihood is individuals may be performing even less relative intensity physical activity than the 23 minutes of absolute intensity physical activity reported by Colley et al. (2018). One potential issue in reporting subjectively measured activity involves people’s awareness of physical activity guidelines and intensities. A recent study investigating physical activity awareness in young males reported that 40% of 776 participants were aware of physical activity recommendations, but only 7% were able to correctly identify moderate intensity physical activity (Vaara et al., 2019). There is, therefore, concern that the percentage of the UK population performing the required level of physical activity as reported by Public Health England (GOV.UK, 2022) could be significantly lower than the report suggests. The high level of error in subjective reporting of both sedentary time and physical activity accumulation (Vaara et al., 2019; Prince et al., 2020), could be significantly overestimating the amount of physical activity being performed, while underestimating the amount of time spent sedentary at a population level.

One of the potential issues in self-reporting physical activity is the subjective nature of the UK national health service (NHS) guidelines. The NHS suggests that moderate intensity “…will raise your heart rate, and make you breathe faster and feel warmer. One way to tell if you're working at a moderate intensity level is if you can still talk, but not sing.” (nhs.uk, 2022). However, how one interprets these guidelines may make it difficult to reach moderate intensity physical activity based solely on these subjective cues. For example:

How warm should one feel during moderate intensity? How would an individual interpret that they are too warm or not warm enough to have reached moderate intensity physical activity? How fast should a raised heart rate be? What does the intrinsic sensation feel like?

Given these uncertainties, it is important to understand how individuals interpret the national guidelines so that they can be communicated most effectively. Therefore, the main aim of this study was to examine how people interpret NHS physical activity guidelines. In order to gain further insight into individual interpretation of physical activity intensity, a qualitative analysis was completed in the form of semi-structured, one-to-one interviews to gain a better understanding of self-reported exercise intensity perception based on NHS physical activity guidelines (nhs.uk, 2022).

7.2 Methods

The study design was pre-registered prior to data collection and can be found at https://osf.io/j39fa. COREQ guidelines were adhered to throughout the reporting of this study (Tong, Sainsbury and Craig, 2007).

7.2.1 Ethics

Institutional ethics approval was obtained from the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull (REF – FHS230). Additional ethical considerations can be found in Chapter 3. Participants in this study were invited to take part in the semi-structured interviews but this was not mandatory and written consent was obtained separately.

7.2.2 Research team and reflexivity

All interviews were conducted by the lead investigator AW, male, PhD student. The investigator established a rapport with participants during the laboratory trials prior to the semi-structured interviews. Participants were aware the semi-structured interviews were being conducted towards the attainment of a PhD degree and were aware that the aim and purpose of the study was to investigate the walking cadence required to reach moderate intensity. The lead investigator's philosophical paradigm was previously discussed in Chapter 3.

7.2.3 Participants

Participants represented a sub-sample of people who were originally recruited from the quantitative study (described in Chapters 5 and 6). Initially, all participants who were recruited for the physical trials performed in chapter 4 and 5 were asked to participate in the semi structured interviews (more detail can be found in chapter 3.2.6). Participants were interviewed directly after completing the final overground trial on their third visit to the laboratory. Interviews were completed in the laboratory where the participant and lead investigator were the only people present. Interviews were completed on campus at the University of Hull. Participants (Table 7.1) were 43.5% female aged 18-65 years (mean [SD] 31 [11] years). Written informed consent to participate in the semi-structured interview was obtained. Participants were made aware that their interview would be audio-recorded, but data would remain anonymous.

Table 7.1 Participant's age, sex, and occupation

Participant	Sex	Age (years)	Occupation	Maximal oxygen consumption (mL·kg^{-1}·min^{-1})
1	M	32	Operations manager	58
2	F	28	Lab technician	36
3	M	32	Energy surveyor	62
4	M	28	Crane driver	57
5	F	41	Medical doctor	47
6	M	40	General Practitioner	52
7	M	24	Student (Sport Science)	42
8	F	29	University lecturer (Sports Therapy)	51
9	M	28	Lab technician	52
10	F	58	Finance assistant	23
11	M	26	Teacher	53
12	F	28	Student (Sport Science)	33
13	F	55	Medical doctor and anaesthetist	28
14	M	49	Professor of Teaching	34
15	F	23	Student (Biology)	53
16	F	24	PhD student (Computer Science)	19
17	F	29	Lecturer (Sports Therapy)	48
18	M	20	Student (Sports Coaching)	44
19	M	18	Student (Languages)	45
20	F	40	Researcher (Cancer)	33
21	M	21	Computer science student	45
22	M	24	PhD student (Geoscience)	34

23	M	19	Jeweller	58

7.2.4 Data collection

Participants were invited to complete a one-to-one interview with the lead investigator. The semi-structured interview guide (Appendix E) accommodated assessing individual responses and comments while enabling the identification of shared themes across participant answers. A combination of open (n=12) and closed (n=9) questions were used for each individual interview, and as the structure of the interview was not limited to the guide, it allowed for additional questioning to gain further insight and clarity when required. The semi-structured interview was initially pilot tested. No repeat interviews were conducted.

The purpose of the core questions centred on obtaining a retrospective assessment of participants' perceptions of UK NHS physical activity guidelines. Specifically, there was direct questioning based on the physical trials performed in the laboratory on the same day, to obtain participants' understanding of 3 key areas: 1) participant's understanding and interpretation of UK NHS guidelines; 2) perceptions of the UK NHS guidelines for moderate intensity, and specifically the intrinsic sensation described by NHS guidelines for moderate intensity (nhs.uk, 2022) and how these are interpreted by participants. The interviews lasted approximately 10-15 minutes, were audio-recorded and transcribed verbatim, and participants were not identified in the recordings or in the transcripts. Five participants were selected for member checking, to check for clarity and accuracy of transcription.

7.2.5 Data Analysis

To understand individual perceptions of wearable technology and nudge theory to guide physical activity, the text was analysed using a thematic analysis based on a 6-stage process (explained in greater detail in Chapter 3) (Braun and Clarke, 2006). This process was used because of its flexibility and potential to deliver rich and complex understandings. A deductive semantic approach to the data coding was used. Data were analysed within the explicit or surface meaning of the data. Responses were explored by the lead investigator AW, involving the following six steps: (1) familiarisation with data, (2), initial coding, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing the report.

7.3 Results

Five main themes were identified with several sub-themes relating to physical activity guidelines and participation and are described in detail below in Table 7.2.

Table 7.2 The five themes and subsequent subthemes.

Theme	Subtheme
Theme 1. Government guidelines: disparity in understanding	
Theme 2. Exercise modalities	- *Exercise descriptors*
Theme 3. Engagement with subjective feeling	- *Focus on breathing*
	- *Social context aids subjectively measured physical activity intensity*
	- *Body temperature consistency*

- *Removing layers*
- *Perspiration*
- *Heart rate subjectivity*
- *Heart rate objectivity: wearable devices*

Theme 4. Escapism when walking

Theme 5. Usefulness of government guidelines

7.3.1 Theme 1. Government guidelines: disparity in understanding

Participants' understanding of UK NHS guidelines showed a vast array of responses. Three of 23 participants correctly identified the cardiovascular components of the government guidelines to be '150 minutes of moderate or 75 minutes of vigorous intensity a week.' (nhs.uk, 2022, p.64). One of 23 participants correctly identified moderate intensity guidelines and the need for weekly resistance exercise:

'Two resistance sessions a week and 150 minutes of moderate intensity physical activity' (participant 12, **aged** 28).

Other participants answers varied widely when asked if they were aware of current government guidelines for physical activity:

> *'No, Government guidelines? 30 minutes a day?'* (participant 3, **aged** 32)
>
> *'No, only because of this study, 20 minutes a day'* (participant 8, **aged** 29)
>
> *'3 to 5 times a week 30 – 60 minutes each time'* (participant 9, **aged** 28)

'10 hours a week' (participant 19, **aged** 18)

'10,000 steps a day' (participant 22, **aged** 24)

'*Only kind of bare bones, kind of 1/2 an hour every day for five days'* (participant 7, **aged** 24)

Several participants took additional probing to gain more insight into their perceptions of physical activity guidelines:

Researcher:	*'Are you aware of any current physical activity government guidelines?*
Participant 10 **aged** 58:	*Vaguely some. Yeah, what you've given me today. So apart from that not otherwise. Apart from, yes, that you should be exercising eating healthily and apart from that,*
Researcher:	*Do you know how many minutes of exercise you should be performing daily or weekly?*
Participant 10 **aged** 58:	*And I thought roughly should be doing half an hour every day, or your 10,000 steps?'*

While several participants were aware there was a time and frequency element to the guidelines, in some form or another, the ability to distinguish what sort of physical activity or intensity was not often discussed unless probed:

'*hour to 2 hours per week'* (participant 21, **aged** 21)

'Something along the lines of half an hour to an hour a day' (participant 23, **aged** 19)

'And I thought roughly half an hour a day' (participant 10, **aged** 58)

'You should be physically active 3 time a week for an hour each' (participant 15, **aged** 23)

'I always thought it was 30 minutes a day' (participant 16, **aged** 24)

It appears that in general participants are not aware of the specific details regarding the government guidelines for physical activity. Most participants were able to give a 'ballpark' figure relating to time and frequency of physical activity completion, albeit, not always in line with the government recommendations, but intensity of that exercise was often unaccounted for.

7.3.2 Theme 2. Exercise modalities

When asked what types of physical activity might be classed as moderate intensity, most participants (19 of the 23) identified walking as a form of physical activity that would adequately reach moderate intensity, while the two other most common physical activity modalities included jogging (12 of 23 participants) and cycling (8 of 23 participants).

'Uh, cycling, uh, walking, running for some people' (participant 3, **aged** 32)

'So brisk walking and cycling and well, depending on speed (participant 009, **aged** 41)

Walking at a pace' (participant 6, **aged** 40)

'Walking jogging at a Moderate pace' (participant 8, **aged** 29)

'A light jog, I guess you could be on a cycle' (participant 9, **aged** 28)

'A brisk walk or a cycle ride' (participant 10, **aged** 58)

'Walking, jogging' (participant 11, **aged** 26)

'Sort of quickly walking, cycling, jogging (participant 18, **aged** 20)

Walking jogging' (participant 19, **aged** 18)

'Brisk walking or a nice cycle something like that' (participant 20, **aged** 40)

Exercise descriptors

A sub-theme that occurred from the discussion of exercise modalities was that several key descriptors were often referred to when participants defined the intensity of the exercise modality:

'Power walk, light jog slow cycle' (participant 1, **aged** 32)

'Fastish walk, a jog or a hike (participant 16, **aged** 24)

'Walking at a pace' (participant 6, **aged** 40)

'Fast walking, swimming, light jog' (participant 12, **aged** 28)

'*Brisk walk, possibly swimming or running'* (participant 13 **aged** 55, 5 **aged** 41)

'Brisk walk' (participant 14, **aged** 49)

'A light jog or, light weight session maybe' (participant 17, **aged** 29)

'Not just ambling to the shops, something with a bit of purpose' (participant 10, **aged** 58)

'Brisk walking or a nice cycle something like that' (participant 20, **aged** 40)

All the participants quoted above defined the walking speed with adjectives to create an emphasis on speed. The use of 'brisk,' 'power,' 'pace' or 'fast' are referred to when describing walking, while jogging was often referred to as 'light'. Additionally, participant 17 **aged** 29 who referred to 'a light weights session,' as a form of moderate intensity physical activity, interestingly, did not identify the resistance component within the government guidelines. Participant 12 **aged** 28, who was the only participant to highlight the resistance sessions in the government guidelines for physical activity, did not identify resistance exercise as a form of moderate intensity physical activity. The comparative differences in adjective used to describe the exercise modalities could be described as antonyms: brisk, fast, power, and pace for walking, as opposed to 'light' and 'nice' for cycling, jogging, and resistance exercise.

Other participants also highlighted that exercise modality may work on an individualised basis.

Participant 7 **aged** 24:	*'There is a, it's hard to tell 'cause it depends what intensity you want to do in that thing? You know if you go canoeing and you kind of go easy or hard or moderate, it's, it's defined by the person.*
Researcher:	*OK, so you don't think there's any specific activity. It's more a case of how hard you do that activity.*
Participant 7 **aged** 24:	*Yeah, It's individualised,*
Researcher:	*So, if you go for a walk for example, could you walk at hard intensity?*
Participant 7 **aged** 24:	*probably, but it would be different to someone else's hard intensity'*

Those participants who identified physical activity intensity to be individualised (participants 7 **aged** 24, 4 **aged** 28), did not identify moderate or vigorous intensity guidelines when asked to describe the government guidelines and were only able to recall the time component.

7.3.3 Theme 3. Engagement with subjective feeling

When participants were asked how they perceived moderate intensity would make them feel, participants identified two clear subjective perceptions. An indication of increased body temperature (18 of 23 participants) and increased breathlessness (19 of 23 participants) were subjective cues most participants referred to.

> '*Warmer, yeah. I'm not breathless, but a higher rate of breathing, breathing affecting my ability to speak freely*' (participant 3, **aged** 32)
>
> *'Shortness of breath*' (participant 4, **aged** 28)
>
> *'I'd expect to feel warmer, feel my heart rate lift and feel a bit out of breath. But still be able to talk'* (participant 009, **aged** 41)
>
> *'Yeah, you will start to be aware that you're feeling warmer. You'll you know you'll get a bit of a sweat developing. I'd expect your breathing rate to be noticeably higher but not an effort, but your breathing rate will increase. You should be more aware of your heart as well"* (participant 6, **aged** 40)
>
> *'But but I'd say sort of a level of exertion, which you're comfortable still to sustain for, you know, a reasonable length of time'* (participant 6, **aged** 40)
>
> *'Definitely warm. I could talk you know, I should be able to at least feel my heart rate. I feel like with my moderate intensity like you should be getting towards the stage where you know, you're on the brink of going into a hard kind of exercise, so you nearly warmed up. Basically, that's how I feel'* (participant 7, **aged** 24)
>
> *'Like you're doing something but not getting too puffed out'* (participant 013, **aged** 29)

'Slightly breathless, so it's, it's not like it's a point where you can't breathe but it's like just noticeable type of thing, and probably warm up a little bit' (participant 9, **aged** 28)

'It'll make you feel a bit warm and possibly a bit short of breath, but you can still talk' (participant 13, **aged** 55)

There is a clear identification of body temperature and breathlessness as a gauge for reaching moderate intensity. Heart rate, although identified by several participants, may be more difficult to use subjectively. Seven of 23 participants identified an increased heart rate as an indicator of moderate intensity.

'You know I should be able to at least feel my heart rate' (participant 7, **aged** 24)

'Start sweating a little bit, heart rate increases' (participant 18, **aged** 20)

'Increase the heart rate increase the body temperature' (participant 21, **aged** 21)

'Feel slightly warmer than normal, and raise your heart rate' (participant 22, **aged** 24)

'You just feel a general sort of pump going on in your body, but nothing too strenuous' (participant 23, **aged** 19)

'*Feel my heart rate lift'* (participant 009, **aged** 41)

'You should be more aware of your heart as well' (participant 6, **aged** 40)

Interestingly, when participants were asked to identify how they would know their heart rate was high enough that they had reached moderate intensity, 7 of 23 participants were able to recognise heart rate as a moderator of physical activity intensity via a wearable device and subsequent heart rate reading while 4 of 23 participants said they were unable to use heart rate as an identifier (described in more detail below).

Focus on breathing

Participants were asked to identify, based on NHS guidelines for moderate intensity physical activity (nhs.uk, 2022), how they knew they had reached moderate intensity from their level of breathlessness, heart rate, and body temperature, specifically 'NHS guidelines suggest moderate activity will raise your heart rate and make you breathe faster and feel warmer, one way to tell if you're working at a moderate intensity level is you can still talk but not sing.' Participants were asked, based on the NHS guidelines, how would you know your breathing was fast enough that you had reached moderate intensity? Several descriptors were used to define breathing at moderate intensity, with the most common answer given was focused on breathlessness.

> *'Shorter breaths'* (participant 1, **aged** 32)
>
> *'You'd be breathing heavier'* (participant 3, **aged** 32)
>
> *'Well, if you start panting more than just normal breathing, and it's a bit laboured'* (participant 10, 58)
>
> *'Slightly out of breath'* (participant 11, **aged** 28)
>
> *'If it's going to be anything that would make me feel that I'm actually exercising properly, it would be more about breathing, I think, it's when I'm aware of it. You know when I'm aware of the fact that I'm breathing faster'* (participant 14, **aged** 49)

‘I’d feel a bit slightly out of breath’ (participant 15, **aged** 23)

‘I'd probably be noticing breathing heavier’ (participant 16, **aged** 24)

‘Well, you’re aware that it’s not regular’ (participant 19, **aged** 18)

‘If I walk to a point where I feel a little bit out of breath then I know that I'm walking as an exercise of intensity rather than just a little stroll’ (participant 5, **aged** 41)

‘I could feel that I'm a little bit breathless. You know, having that kind of slight breathlessness that you would associate with working harder I'm not the kind of breathless that you know that you're like gasping for air or anything like that. But yeah, just a bit faster’ (participant 20, **aged** 40)

‘*Uhm, you switch from breathing through your nose, to your mouth’* (participant 22, **aged** 24)

‘Normally I prefer my nose, but if I'm doing any kind of exercise that raises the heart rate, I have to then breathe through my mouth, which is when I would probably have switched to moderate’ (participant 1, **aged** 32)

‘I suppose I have a lower scale for that, I have asthma so sometimes our breathing can just generally be heavy in certain seasons anyway, so it won't be the heaviness of it would just be the repetitions of it. The more I'm actually feeling myself having to breathe during a bit of exercise or something like that’ (participant 23, **aged** 19)

As stated by participant 23, there may be instances where the use of subjective breathing rate is not suitable for some individuals with respiratory conditions. Descriptors such as ‘faster’, ‘heavier’, and ‘breathless’ were most often used to describe the subjective phenomena of breathing rate during moderate intensity.

Social context aids subjectively measured physical activity intensity

Walking with a partner may have additional benefits in one's ability to assess breathing rate.

> *'So, there's that ability to talk, which if you're on your own, might be difficult to assess if you're walking with someone else with intent and you're trying to have a conversation, and you'd be aware if you're feeling a little bit out of breath'* (participant 5, **aged** 41).
>
> *'No to heart rate, no to warmer, but yes, ability to talk or would usually go like for a walk with a friend or something like that, but we would walk with purpose, but we'd be talking'* (participant 013, **aged** 29).
>
> *'I'm breathing faster or aware of the fact that I'm trying to have a conversation but it's becoming more and more difficult or not more difficult, but it's not that dramatic, but I'm more you know, you're aware of it and I think it's that I think it's being aware of my breathing rather than just walking without thinking about it, you're aware of it'* (participant 14, **aged** 49).

All participants quoted above perceived the ability to talk to be a useful guide in indicating moderate intensity. However, several participants highlighted the 'able to talk but not sing' component of the NHS guidelines to be somewhat confusing or unusable.

> *'I feel like I'd be able to sing going around that sort of 40% heart rate reserve. Or you know that kind of intensity, so I don't think it works for everyone'* (participant 7, **aged** 24)

‘*No, only because you could still sing whilst jogging if you really wanted to. I wouldn't sound as good like. You know but you could still sing if you wanted to*’ (participant 12, **aged** 28).

I can talk and I can still sing, so I need to work harder. That's all I thought anyway, from hearing those guidelines I thought was a bag of rubbish’ (participant 9, **aged** 28).

‘I think I could probably gauge it, but at the same time I'm not going to be walking down the street trying to sing in public, so…’ (participant 16, **aged** 24).

Body temperature consistency

The same question was also asked for body temperature: ‘How would you know you are warm enough that you have reached moderate intensity? Two very clear sub-themes arose, which were:

Removing layers

‘If I feel like I need to take a layer off, and so I'm quite a cold person generally, so if my hands are warm, I know that I'm definitely I have warmed up’ (participant 009, **aged** 41).

‘But then it means that I take off one layer of clothing, which I do sometimes when I'm walking’ (participant 13, **aged** 55).

‘If I walk, if I walk with just a slow pace, I can't. I can never walk somewhere with a jumper on, I gotta take the jumper off and put it in my bag, even if it's freezing outside. I get hot’ (participant 15, **aged** 23).

'If I feel like I need to take a layer of clothes off I need to slow down, cool down' (participant 16, **aged** 24).

'Because usually I layer up so, how many layers I have on I have to, you know, unzip my outer coat or my hoodie or something like that' (participant 20, **aged** 40).

'Probably when it starts to be a bit uncomfortable in my clothes I' say yeah, you want to take a layer off? Yeah, that's when I'd think I'd reached moderate intensity' (participant 23, **aged** 19).

Perspiration

'Started sweating that sort of stuff' (participant 7, **aged** 24)

'Don't know, start sweating I guess yeah, yeah. I think sweat perspiration a little bit' (participant 10, **aged** 58)

'Well, I'm aware that I'm wearing a t-shirt, I get a clammy feeling against your t shirt' (participant 19, **aged** 18).

'Yeah, you will start to be aware that you're feeling warmer. You'll you know you'll get a bit of a sweat developing' (participant 6, **aged** 40).

However, body temperature, sweating, and the need to de-layer as an indicator or physical activity intensity has some limitations, highlighted by participants:

'I think it's just. It's just how you feel. I mean, it's a it's an odd one with the with that guideline. 'cause it does depend a lot on the ambient temperature as well' (participant 14, **aged** 49)

'If I am walking to a location that I've got to be in and around people, then I don't want to be sweaty' (participant 12, **aged** 28).

'Nothing too hot, Then I'll slow down' (participant 16, **aged** 24)

As participants have described above, there are several contributing factors that impact subjective ability to use body temperature as a gauge of intensity. Additionally, participants' perception can often be that sweating is undesirable and wish to avoid sweating when in public.

Heart rate: subjective

Finally, the same question was asked for heart rate: "How do you gauge your heart rate increasing, what would moderate intensity heart rate feel like?"

> *'Because I have really bad circulation. So once my hands get warm then I know that I raise my heart rate enough to actually get the blood to them'* (participant 2, **aged** 28).
>
> *'You can kind of feel it as well, just in your wrist a little bit, It's not like, it's not like, you've been sprinting or running and you finish and you can actually feel it in your chest, it's kind of like every so often you'll have a little bit of a kind of like dumb, dumb, and it's a bit like you know you can feel it*' (participant 7, **aged** 24).
>
> *'Feeling your heart rate increase, like the feeling of your pulse in your neck'* (participant 19, **aged** 18).
>
> *'Just it, your heart feels like it's pumping a lot faster than, and sometimes I can feel it in my neck'* (participant 21, **aged** 21).
>
> *'I suppose when you become aware of your heart rate being increased above its regular like background noise'* (participant 22, **aged** 24).

Heart rate objectivity: wearable devices

Seven of 23 participants highlighted the use of wearable technology in improving their ability to identify physical activity intensity objectively.

> *'So, I'm aware of my heart rate. I wear a watch which tells me what its is'* (participant 5, **aged** 41)
>
> *'I think I'm pretty aware of heart rate and roughly you know my resting heart rate is around 60, so I think I'll be I do sometimes check it out when I'm exercising as to what it is as a ballpark figure, and the watch normally, would tell me what my heart rate was at that time so'* (participant 6, **aged** 40).
>
> *'I do look at my heart rate, but that's because I've got my Fitbit watch'* (participant 7, **aged** 24)
>
> *'If I set my watch or my Fitbit for that, I'm out going out for a walk, then it'll buzz at me, and I'll let me know when I'm in different heart rate zones but It's more about objective measure as opposed to a subjective feeling. If I'm walking to the, if I'm walking to work or the shops, I know I'm walking a little bit faster, so I'll just assume my heart rate is, you know up to around one 110 or something like that. It's generally kind of what I expect it to be for moderate'* (participant 20, **aged** 40)

All the above referenced using heart rate as an objective measure of physical activity intensity, however participants' ability to use the subjective guidelines to perform moderate intensity may not be as easy, with 4 of 23 participants unsure of their ability to use heart rate subjectively:

> '*I didn't feel my heart rate rise'* (participant 13, **aged** 55)

'Not really, so I don't think I've thought about heart rate so much' (participant 16, **aged** 24)

'No to heart rate, no to warmer, but yes, ability to talk' (participant 013, **aged** 29)

7.3.4 Theme 4. Escapism when walking

Participants were asked what they thought about when walking, with a distinct theme of escapism being evident, with 12 of 23 participants engaged in daydreaming.

> *'Think about nothing. Just think about it, nothing really, walking is good stress relief for me'* (participant 4, **aged** 28)
>
> *'I'm not really thinking much'* (participant 013, **aged** 29)
>
> *'I'll be thinking about everything around me. Don't be thinking about what intensity I'm walking up because I'm not the sort of person who thinks walking is exercise'* (participant 9, **aged** 28)
>
> *'If you amble into the shops or doing like country walk you would probably, you'll walk at a slower pace and just take in the scenery'* (participant 10, **aged** 58)
>
> *'Just leisurely walking and daydreaming that sort of stuff'* (participant 11, **aged** 26)
>
> *'Daydreaming thinking, thinking, active thinking. But basically, I'm thinking about the task to do most of the time. If I watch my thoughts, I'm thinking about task to be done'* (participant 13, **aged** 55)
>
> *'Thinking about daily life as opposed to thinking about the purpose of your exercise'* (participant 14, **aged** 49)
>
> *'Like just my random thoughts, I won't be thinking about walking pace'* (participant 17, **aged** 29)

'And then you think about what's happening at school and what different tasks, I tend to walk as a sort of a mindfulness thing' (participant 19, **aged** 18)

'Walking, active commuting so walking to work. I'm usually thinking about work or what has to happen that day or something along those lines' (participant 20, **aged** 40)

'Sometimes I just try and recall either what I'm doing in the day or what I've just done to try and make sure I've understood like lecture content' (participant 21, **aged** 21)

'Normally I'm answering emails in my head or trying to work on whatever their actual PhD, work and yeah it does change 'cause when I'm out to do things socially. I think about that instead of answering emails' (participant 22, **aged** 24)

While 7 of 23 participants were engaging with the scenery around them.

'Normally it's looking at scenery. And yeah. It's just like not paying attention to actual walking. Just looking around' (participant 7, **aged** 24)

'But at times I remind myself to be present to watch the flowers, to enjoy things' (participant 13, **aged** 55)

'If you're on like a hike or something, then, I don't know, yeah just thinking about where you're going, what you are looking at' (participant 16, **aged** 24)

'Normally it's sort of walking to get somewhere. I'm just kind of listening to music. I have more focus on music and kind of where I'm going, I sort of look at the world around me more like a daydreaming' (participant 18, **aged** 20)

In contrast, only 2 of 23 participants were considering increasing their step count as their focus when walking, and 2 of 23 participants were aware of walking with purpose to gain more benefit from aerobic activity.

> *'Depending on how much exercise I have done that day, I would be pushing my pace a little bit, I don't tend to dawdle'* (participant 5, **aged** 41)
>
> *'I will be more aware of trying to maintain it a consistent fast enough pace to for the intention of raising my heart rate'* (participant 6, **aged** 40)

7.3.5 Theme 5. Usefulness of government guidelines

Finally, participants were asked their thoughts on the government guidelines for moderate intensity physical activity:

> *'These are really hard questions'* (participant 8, **aged** 29)
>
> *'Hearing those guidelines, I thought was a bag of rubbish (participant 9,* **aged** *28)*
>
> *I think it's pretty subjective, I think'* (participant 20, **aged** 40)
>
> *'It makes sense to me whether it makes sense to people who aren't used to exercising it's another matter, I suppose'* (participant 5, **aged** 41)
>
> *'They are a useful starting point, but they're so open to interpretation'* (participant 6, 40)
>
> *'Not particularly useful'* (participant 16, **aged** 24)
>
> *'Probably not, I don't think they are useful'* (participant 1, **aged** 32)
>
> *'I think they're a bit vague across the spectrum for people. I think a lot of people probably don't know what moderate intensity is so it's probably quite difficult to gauge from these'* (participant 3, **aged** 32)
>
> *'No, I'm not able to interpret them'* (participant 8, **aged** 29)

'I would say not really because everybody is different' (participant 10, **aged** 58)

'I don't think so, but definitely it's only shortness of breath, so, maybe it's telling me that if you are short of breath, you're doing moderate exercise. But I don't know that I do find them useful' (participant 13, **aged** 55)

'I'm not sure they are, I think it's the, I think the frequency is useful and the length of time is quite useful. I think the definition of moderate is quite a difficult one, it's quite difficult to pin down I think this is the only real parameter that I'm aware of that is when you start thinking about being breathless. I'm not sure what you would have instead, but I I'm not sure it all that helpful' (participant 25, **aged** 49)

'They're a starting point, I suppose. I don't think based on what I know there maybe not as useful as they could be, they are quite subjective' (participant 20, **aged** 40).

'Not specially 'cause I wasn't aware of them before the study' (participant 22, **aged** 23)

'Well, so not my own sort of experience for the NHS ones, probably not, because I've never really thought about them. Like I said, I couldn't tell you what they were. It would make sense to me that they would cause moderate exercise, but for my own day-to-day life, I wouldn't be gauging my own activity compared to that sort of guideline' (participant 23, **aged** 19).

As this section highlights, participants reported that the NHS guidelines are open to considerable interpretation and subjective evaluation.

There was no deviation from the pre-registration.

7.4 Discussion

7.4.1 Theme 1. Government guidelines: disparity in understanding

This study investigated perceptions and understanding of NHS and UK government guidelines for physical activity (nhs.uk, 2022) in participants reflecting a range of ages and demographics. Five main themes were identified. The first theme 'NHS guidelines: disparity in understanding' revealed participants were either unaware of the NHS guidelines to physical activity (nhs.uk, 2022) or unable to identify them correctly. A large proportion of participants were unaware or unable to report the level of exertion that is required to meet the physical activity guidelines. Participants were aware that a time recommendation was prescribed but the detail in timing was a spectrum ranging from 90 minutes to 600 minutes a week. Although a wide variation in answers existed, the most common duration and frequency given was that equating in some form or another to 30 minutes per day. A lack of understanding of physical activity guidelines at a population level is common. Vaara, Vasankari, Koski, & Kyröläinen, (2019) reported that of 776 young men in Finland, 40% were aware of government guidelines, but only 7% correctly identified the aerobic physical activity guidelines, 25% correctly identified the resistance exercise component, and only 4% correctly identified both components. Additionally, a national survey of 2860 UK adults reported that 18% were able to correctly recall current physical activity guidelines, with those coming from a disadvantaged background the least knowledgeable in this area (Knox et al., 2013).

7.4.2 Theme 2. Exercise modalities

Participants identified three common activities that may align with moderate intensity. Walking (n=19), jogging (n=12) and cycling (n=8) were the most common responses, although participation in the physical trials consisted of walking trials, which may have created bias in participants' perception of physical activity modalities suitable for moderate intensity, as participants were aware the study was designed to obtain moderate intensity via walking. These exercise modalities in some way replicate commonalities at a population level, as walking is the most common form of physical activity completed in the UK and cycling, running/jogging also make the top 10 (Sport England, 2020). A sub-theme from this analysis emerged in the use of adjectives to describe exercise modality intensity. Walking was almost always referred to as brisk, with power, pace, or fast. Whereas cycling and jogging were described with adjectives including nice, light, and steady. These descriptors may be influenced by government guidelines. Brisk walking is an example of moderate intensity physical activity used in NHS guidelines (nhs.uk, 2022). Additionally, authors have reported self-rated walking pace descriptors are near standardised as 'very slow, slow, average or brisk/fast' (Syddall et al., 2015; Stamatakis et al., 2018). As walking is generally associated with moderate intensity, in this study 19 of 23 participants identified walking as a form of moderate intensity physical activity, using adjectives to describe walking at speeds such as brisk may encourage people to walk above their normal walking speed.

Descriptors for other forms of physical activity may also indicate a greater understanding of NHS guidelines than participants perceive. NHS guidelines refer to 'cycling gently or on level ground' (NHSinform, 2022) as a form of moderate intensity, which may indicate why participants in this study used such descriptors to indicate physical activity intensity when describing cycling intensity. According to NHS guidelines (nhs.uk, 2022), jogging is not identified as a form of moderate intensity and running is used as a form of vigorous intensity. Potential reasons for why NHS guidelines identify running as vigorous intensity and do not identify jogging as a form of moderate intensity physical activity, may be that jogging at moderate intensity is unattainable, due to the cadence required to enable jogging, eliciting vigorous intensity. Kilpatrick et al., (2009) investigated participants' ability to jog at moderate intensity, with participants instructed to maintain an RPE (6-20 Borg scale) of 13 (moderate) while jogging. Mean %HRR was 77 ± 17, considerably over the 40-59 %HRR criterion moderate intensity threshold (Liguori, 2022), which suggests jogging may be too vigorous to attain moderate intensity. In addition, Schnohr et al., (2015) referred to light joggers as slow or average pace. This descriptor was associated with a running speed of approximately 5 mph, (~8km·h^{-1}) which corresponded to 6 METs, an absolute intensity on the threshold of moderate and vigorous intensity according to ACSM guidelines (Liguori, 2022). Obtaining moderate intensity from jogging is more difficult, and more suited to vigorous intensity, which may explain why NHS guidelines do not include jogging as part of their moderate intensity examples. This may have implications, as several participants in this study associated jogging with as a modality that would attain moderate intensity. Over half of the participants in this study identified jogging as a form of moderate intensity physical activity. While it is likely participants will reach an intensity that is beneficial for cardiorespiratory health from jogging (Swain and Franklin, 2002; Al-Mallah, Sakr and Al-Qunaibet, 2018), as discussed previously (Chapter 2) adherence and lack of enjoyment when performing vigorous intensity physical activity may outweigh the potential benefit (Zenko, Ekkekakis and Ariely, 2016; Ekkekakis et al., 2023). This might indicate why jogging is not a form of physical activity advised in NHS guidelines for moderate intensity, as the intensity is more likely to be vigorous and thereby may reduce adherence.

The use of descriptors to identify exercise modality intensity may play a significant role in physical activity guidance. Participants often used a descriptor when defining an exercise modality associated with moderate intensity. Defining useful descriptors to aid physical activity guidance may help the population more accurately perform moderate intensity physical activity, and more research on this topic is warranted.

Several participants identified a necessity to individualise exercise intensity, suggesting cardiorespiratory health may impact one's ability to obtain moderate intensity from some forms of exercise modalities, or if CV health is poor, those modalities associated with moderate intensity may result in vigorous physical activity. This perception that RPE is impacted by an individual's level of CV fitness is well supported by literature (Felts, Crouse and Brunetz, 1988; Berry et al., 1989; Garcin et al., 1998; Garcin, Mille-Hamard and Billat, 2004), which suggests that identifying the same moderate intensity modalities and descriptors may not be suitable for all individuals. Fitzsimons et al., (2005) investigated this concept: two groups of women, one young (20-23-year-olds) and one older (75–83-year-olds) were instructed to complete walking trials under slow, comfortable, brisk, and fast instruction. During brisk and fast walking trials, older women walked approximately 20% slower than the younger group, but oxygen consumption averaged 67% VO_{2max} compared to the younger group who averaged 45% VO_{2max}. According to ACSM guidelines (Liguori, 2022) the older group elicited an oxygen consumption above the vigorous threshold compared to the younger group who only reached light intensity. As previously reported, cardiorespiratory fitness plays a key role in the cadence required to reach moderate intensity (Abt et al., 2019)(Chapter 5). Therefore, the speed required during walking to reach moderate intensity for those with good cardiorespiratory health might be deemed brisk, but for those with poor cardiorespiratory health could be deemed slow.

7.4.3 Theme 3. Engagement with subjective feeling

The NHS has tried to combat the inconsistency in intensity being performed for generic exercise descriptors such as a 'brisk walk' with subjective feeling scales for moderate intensity, incorporating subjective feelings for breathlessness, body temperature, and heart rate to guide people to exercise at the correct intensity from intrinsic feeling (nhs.uk, 2022). When participants were asked about the guidelines in this study (raised heart rate, breathing faster, and feeling warmer), another key theme that emerged from the data was 'Engagement with subjective feeling'. Participants' ability to identify moderate intensity from intrinsic feelings resulted in two sub-themes. Participants were asked how they would know their breathlessness was adequate to reach moderate intensity. Common responses included breathlessness, deep breathing, and shortness of breath, as descriptors for breathing at moderate intensity. Participants 22 **aged** 24 and 2 **aged** 28, identified a transition from nose breathing to mouth breathing as an indicator of moderate intensity. Very little research exists on the intensity of exercise that elicits the switching point from nasal to oronasal breathing, and whether this is a suitable indicator of moderate intensity. Niinimaa, Cole, Mintz, & Shephard, (1980) investigated this phenomenon in 30 healthy adults. Although no relative measure of exercise intensity was monitored, RPE was obtained and at the switching point mean RPE was 13.2 ± 2.2 (moderate intensity). However, the switching point may not be a suitable tool by which to gauge moderate intensity for all individuals. According to Niinimaa et al., (1980), 13% of participants were identified as mouth breathers (who performed mouth breathing at rest) and 17% of participants did not perform any mouth breathing throughout the exercising trials. However, as a clear indication of intensity, the switching point may offer a suitable transition to identify moderate intensity which may be clearly understood by many people, but additional research is warranted. Another indicator of physical activity intensity was one's ability to talk, which formed a sub-theme entitled 'social context aids subjectively measured physical activity intensity'. The ability to hold a conversation while exercising, but while experiencing some breathlessness, was often associated with moderate intensity. Social factors have often been suggested to influence physical activity (Shelton et al., 2011; Espernberger, Fini and Peiris, 2021) and also an additional benefit associated with physical activity (Dionigi, 2007). In this instance the talk test is a well-established method of monitoring physical activity intensity (Shafer et al., 2000; Reed and Pipe, 2014) and an observation associated with breathlessness by those participants who often walk with social interaction. The NHS guidelines refer to being able to hold a conversation but not sing (nhs.uk, 2022) as part of their guidelines for moderate intensity. While the talk test is well established, and participants found it useful, the concept of singing while performing physical activity, in this study, was met with uncertainty and in some cases heavily scrutinised by participants. Research has indicated that in untrained participants, singing (without performing physical activity) may induce the same acute physiological responses as walking at 4 $km \cdot h^{-1}$ (Philip et al., 2021). Thus, in untrained populations it is likely that singing during walking may contribute to an intensity close to moderate intensity and may impact its effectiveness as a measure. Additionally, participant 16 **aged** 24 identified it as an impractical measure that they would refuse to use in a social setting, for embarrassment or as to not draw attention to themselves while in a public space.

Body temperature led to two sub-themes when describing subjective moderate intensity. These were ‘removing layers’ and ‘perspiration’. The usefulness of removing layers to identify moderate intensity is limited by several factors, including ambient temperature and number of layers and thickness of clothing worn. Sweating also has a number of implications as guidance for reaching moderate intensity, as there are a number of variables that impact sweat rate such as layers of clothing, external temperature, and humidity (Baker, 2017). Self-reported exercise induced sweating has previously been used to measure physical activity intensity in coronary artery disease patients (Gruner, Alig and Muntwyler, 2002). Data were obtained via questionnaires, and exercise thresholds were categorised as METs (light <4.0, moderate 4 – 5.9, intense >6 METs). The frequency of self-reported exercise induced sweating was associated with both moderate and intense physical activity. Interestingly however, is the sweat rate reported for brisk walking; of 233 participants, 165 rarely associated sweating with brisk walking, whereas only 15 participants reported sweating when performing brisk walking as a daily occurrence.

These findings are of interest to the current study as a sub-theme that arose from body temperature, and the ‘feeling warmer’ NHS guideline, was sweating as an indication of achieving moderate intensity. Participants in this study associated perspiration, slight sweating, and clamminess as an indicator of reaching moderate intensity physical activity. However, based on the findings of Gruner et al. (2002) this may be a poor indicator for moderate intensity. However, Gruner et al. (2002) used METs to quantify exercise intensity, which may have underestimated physical activity intensity (Chapter 4). In addition, self-reported activities that are strenuous enough to produce sweating have been reported in healthy male adults (Kohl et al., 1988). Three hundred and seventy-five men were asked via questionnaire to identify 'How many times a week do you engage in vigorous physical activity long enough to work up a sweat?' Those who reported sweating three or more times a week during physical activity were associated with improved cardiovascular fitness compared to counterparts who sweat less than three times a week during physical activity.

There is evidence to suggest a linear relationship exists between exercise intensity and sweat rate (Baker et al., 2019). However, individualised sweat rates may impact the ability to use sweating as a means of exercise intensity guidance, as inter-individual variation differs drastically (Holmes et al., 2016). For women this may be more difficult, as the phase of a menstrual cycle may affect sweat rate, which may impact its usefulness as a guide for physical activity intensity (Ichinose et al., 2009).

Using sweat rate as a method to distinguish between moderate and vigorous intensity may also have limitations as a number of physical activity intensity questionnaires do not distinguish a difference between moderate and vigorous intensities (Kohl et al., 1988). The NAHNES health and nutritional status study tried to distinguish the difference in sweat rate associated with moderate and vigorous intensity. Moderate intensity sweating was referred to as a 'light sweating' and vigorous intensity was referred to as 'heavy sweating' (Raiber et al., 2019). However, validation of these different sweating descriptors to distinguish exercise intensities is unclear.

There is also a clear limitation with the use of sweat rate to guide physical activity. Three participants from this investigation highlighted the need to avoid sweating during walking, due to disliking the sensation or for socialising purposes. Participants highlighted they would actively choose to reduce walking speed if they started to perspire. There are also social considerations to sweating that may impact people's willingness to pursue a physical activity intensity that causes sweating. Often sweating can hold negative symbolic connotations reflecting an unhealthy body image, which affects individuals perceived social image and self-presentation, which in some circumstances can be anxiety-evoking (Rossing, Ronglan and Scott, 2016).

Participants in this study are interpreting NHS guidelines for an increase in body temperature distinguished by two main indicators, perspiration and removing layers. The usefulness of this interpretation is problematic, as there are too many extrinsic and inter and intra-individual variables that impact perspiration. Removing layers also has implications for its implementation as an exercise guidance tool, for obvious reason, especially in the UK where seasons are very distinguishable and the changes in weather may have a large impact on the number of layers worn when walking. It is, therefore, unlikely that perspiration and the need to delayer would make useful subjective exercise guidance for population level messaging.

The final subjective measure participants were asked to gauge moderate intensity from, based on the NHS guidelines, was heart rate. Participants were asked:
'*How do you gauge your heart rate increasing, and what would moderate intensity heart rate feel like?'*

There were two sub-themes identified from this measure: subjectivity and objectivity. Participants identified the ability to feel heart rate in several anatomical locations including the wrist, chest, and neck. While this may seem plausible at maximal or near maximal intensity the likelihood participants are able to feel their heartbeat in these locations during moderate intensity seems implausible. Yamaji, Yokota and Shephard, (1992) investigated the ability to perceive heart rate before and after a training intervention in six young male university students. Participants performed 3 modes of exercise: cycle ergometer, treadmill running, and stairmill climbing, while ECG heart rate monitoring was recorded. Participants performed the three exercise modalities in the laboratory on three separate occasions. During laboratory visits participants performed an incremental step protocol up to maximal intensity. Intensity increased every three minutes by 30 watts (starting at 30 watts), 1 $km \cdot h^{-1}$ (starting at 10 $km \cdot h^{-1}$), and 5 $m \cdot min^{-1}$ (starting $m \cdot min^{-1}$) for the cycle ergometer, treadmill and stairmill trials, respectively. At the end of each three-minute stage participants were asked their perceived heart rate. Participants then performed 13 weeks of running training for two hours per day, three to four days a week. During sessions participants compared their perceptions of heart rate with values observed on a wrist-mounted pulse monitor with chest strap electrodes. After 13 weeks of training, the laboratory protocol was repeated. Results indicated that on first visit to the laboratory participants perceived heart rate had an absolute mean error of 11.1 (5.5) $beats \cdot min^{-1}$, 25.9 (11.4) $beats \cdot min^{-1}$, 21.4 (16.7) $beats \cdot min^{-1}$, at 100 $beats \cdot min^{-1}$ for the bicycle ergometer, treadmill, and stairmill trials, respectively. At 140 $beats \cdot min^{-1}$ the mean absolute error in heart rate was 12.4 (6.5) $beats \cdot min^{-1}$, 18.2 (2.8) $beats \cdot min^{-1}$, 20.3 (10.7) $beats \cdot min^{-1}$, for the bicycle ergometer, treadmill, and stairmill trials, respectively. This may indicate why the use of heart rate as a subjective measure may be difficult to perceive, especially without any training or educational process. Even with a 13-week training program, Yamaji, Yokota and Shephard, (1992) found participants mean absolute error at 100 beats·min^{-1} was 9.1 (6.9) beats·min^{-1}, 13.2 (6.5) beats·min^{-1}, 26.3 (12.1) beats·min^{-1}, for the bicycle ergometer, treadmill, and stairmill trials, respectively. And at 140 beats·min^{-1} mean absolute error was 7 (6.7) beats·min^{-1}, 8.5 (3.4) beats·min^{-1}, 13.7 (3.9) beats·min^{-1}, for the bicycle ergometer, treadmill, and stairmill trials, respectively. Several participants in this study highlighted that they were unable to feel their heartbeat or have not previously thought about using the heartbeat feeling to guide exercise intensity. Its usability within population exercise guidelines seems improbable and may need amending or disregarding for future use as a subjective measure alone.

One potential barrier for using subjective measures is a lack of understanding, in part due to being unaware such guidelines exist. It is clear from this investigation that participants were unaware of the specific guidance published in the NHS physical activity guidelines, and this may be a barrier across populations. Bopp et al. (2007) investigated African Americans' understanding of physical activity participation, specifically: 1) lack of knowledge about exercise, and 2) lack of awareness of the physical activity required to meet recommended activity levels, which were two themes obtained from the focus group indicating participants were unaware of how to effectively exercise. Participants who are guided via simple objective measures may increase MPA more so than those using subjective means. Bouchard et al., (2013) investigated an 8-week intervention with three intervention groups: manual pulse, heart rate monitor, and pedometer. Participants using an objective measure of physical activity (heart rate monitor and/or pedometer) increased their total aerobic exercise time compared to those measuring pulse rate manually without the use of an external device. Additionally, participants across all three interventions did not improve their ability to correctly identify moderate intensity physical activity post-intervention, even after having a training day prior to the 8-week intervention where they were educated on how to achieve moderate intensity while using their device or measurement method. The evidence from this study identified similar themes to Bouchard et al. (2013) indicating that participants struggle to interpret the NHS guidelines for moderate intensity physical activity effectively. Chapter 6 highlighted this, as only 50% of participants were able to walk at moderate intensity when instructed, via NHS moderate intensity guidelines.

7.4.4 Theme 4. Escapism when walking

Finally, a key theme identified by participants when they were asked what they thought about when walking was ‘escapism when walking’. Many participants were daydreaming, thinking about daily tasks, or were focussing on the scenery around them. It is common for walking to be considered as a thought-provoking activity, when performing light or moderate exercise. A systematic review analysing brain activity when walking found that walking increased brain activity in the frontal cortex, the area of the brain responsible for executive function such as planning, organising and self-monitoring, and in the pre-frontal cortex the area of the brain responsible for cognitive control function and dopamine, influencing attention, prospective memory and cognitive flexibility (Hamacher et al., 2015). This may validate why participants daydream or think about daily tasks that need completing, as walking heightened brain activity that enables focus and potentially improves one’s ability to problem solve or generate ideas. Walking has also been associated with creative thinking and has the potential to improve creative output by as much as 60% (Oppezzo and Schwartz, 2014). This may indicate why participants in this study lack focus on walking intensity or the ability to walk with purpose, as they use walking as a means of escapism. The locomotor task of walking is a simplistic movement that requires very little cognition, enabling the opportunity to focus on additional tasks other than the walking itself (Oppezzo and Schwartz, 2014).

7.4.5 Theme 5. Usefulness of government guidelines

The themes identified above provide evidence for the usefulness of wearable devices for helping people exercise at the correct intensity when the purpose of the activity is to gain the associated cardiorespiratory benefits. It is clear from the evidence of this study, that participants on the whole do not consider government guidelines when performing walking as physical activity, and often find themselves submersed in thought, as opposed to concentrating on the intrinsic feeling of exercise and physiological cues such as breathing rate, body temperature, and heart rate to ensure they are walking at a speed that would facilitate moderate intensity physical activity. It would therefore seem that to obtain moderate intensity accurately, continual guidance that can be offered via wearable technology may be of use in directing users to the correct physical activity intensity.

7.5 Conclusion

Overall, this study presents a useful picture of people's perceptions of NHS physical activity guidelines and how they are interpreted. The findings provide a basis for further exploration of the population's ability to subjectively identify moderate intensity and identify useful intrinsic feeling of physiological markers that identify moderate intensity accurately and allow for a better interpretation at a population level. This study recognises there will always be a diverse range of interpretations when guidelines use subjective feeling to identify physical activity intensity but offers an opportunity to address exercise guidelines to distinguish intensity thresholds more accurately.

8. Nudges used to promote physical activity intensity: A qualitative study

8.1 Introduction

Lack of physical activity at a population level is fast becoming a global health problem, with physical inactivity now the fourth leading cause of death worldwide (WHO, 2022). The benefits of physical activity, and consequences of inactivity, have been extensively investigated (Freitas et al., 2018; McKevitt et al., 2020; Silva et al., 2020; Sallis et al., 2021). The need to perform physical activity to reduce the risk of disease is well documented (Samitz, Egger and Zwahlen, 2011; Ramakrishnan et al., 2021). However, the abundance of evidence that identifies the benefits of physical activity is not having the desired affect at a population level. Currently 1 in 4 men, and 1 in 3 women, do not perform enough physical activity to maintain good health (who.int, 2022a). Further, there have been no improvements in global physical activity levels since 2001, and in high-income countries the number of people who do not meet the physical activity guidelines has increased by 5% (Guthold et al., 2018).

One strategy to increase adherence to physical activity is with wearable technology. Wearable technology has the potentially to help people increase their physical activity (Brickwood et al., 2019; Blount, McDonough and Gao, 2021; Singh, Zopf and Howden, 2022), but very little longitudinal evidence on the long-term promotion of physical activity, and thus behavioural change via wearables, exists (Brickwood et al., 2019). Additionally, the current bed of literature has investigated devices that, although classed as wearables, use outdated technology with little to no user interaction. For example, a device that records physical activity such as step count only and that does not have a screen. A meta-analysis

(Brickwood et al., 2019) of 26 papers highlighted only one intervention study (Thorndike et al., 2014) that used a commercially available wearable device (Fitbit) that may offer some user interaction in giving participants live information as they wear the device during physical activity. A more recent review (Singh, Zopf and Howden, 2022) highlighted an increased number of research investigations using commercial wearable devices as a method of improving physical activity in cancer survivors. Nine of 35 studies used commercially available wearable devices (7 Fitbit, 1 Garmin, 2 Polar). Acceptability relating to the use of physical activity devices was assessed in 6 of these studies, with overall satisfaction for the Fitbit rated at 88 – 90%.

One behavioural change mechanism that more modern wearable devices include is ‘nudges’ (Dhanasekaran et al., 2022). Nudges denote a method of influencing personal choice, without limiting their options or creating restrictions or rules (Schmidt and Engelen, 2020). Instead, cues are provided to alter the person’s decision-making context and support the user by giving feedback, structuring complex choices, or providing incentives (Thaler, Sunstein and Balz, 2012). The use of nudge theory plays an integral role in everyday life, from shopping habits to encouraging use of stairs instead of lifts, which are known as analogue nudges. Technology such as smartphones or computers, provide digital nudge notifications potentially modifying our behaviour. For example, notifications that allow us to respond to messages and emails more promptly and provide reminders of meetings via e-calendars are all examples of digital nudge theory.

Nudge theory can has been reported to successfully alter behaviour to promote physical activity (Mamede et al., 2021; Forberger, Wichmann and Comito, 2022). However, to date there is very little research on the integration of nudge theory and wearable technology in promoting physical activity outcomes. It is possible for wearable technology to enhance physical activity outcomes by nudging the user, as it is in their close proximity to the body and has the ability to do this via haptic vibrations and sounds (Ogbanufe and Gerhart, 2017). However, a recent review highlighted this lack of integration between wearable devices and nudge theory to promote physical activity (Forberger, Wichmann and Comito, 2022). Eighteen studies used nudge theory interventions to promote physical activity, of which 12 studies promoted physical activity via analogous methods. Four studies employed messenger feedback on step goals and physical activity levels via digital methods, however, no interventions incorporated wearable devices to deliver nudges and prompt physical activity simultaneously in a bid to alter the physical activity being performed in that moment. However, these authors still reported that nudge theory could help reduce sedentary time and promote physical activity.

Some possible reasons for the lack of research incorporating/using wearable devices and their ability to prompt physical activity via nudges may be partly due to the apprehension of artificial intelligent digital nudging (Wagner, 2021), and the influence of choice architect (i.e., someone or something that influences the choice of others by organising the context in which people make decisions) (Thaler, Sunstein and Balz, 2012). It is therefore of importance to identify user perceptions of nudges to promote physical activity via wearable technology. Therefore, the aim of this study was to explore participant's views on wearable technology and the application of nudge theory to guide exercise intensity.

8.2 Methods

The study design was pre-registered prior to data collection and can be found at https://osf.io/j39fa. COREQ guidelines were adhered to throughout the reporting of this study in line with accepted guidelines (Tong, Sainsbury and Craig, 2007).

8.2.1 Ethics

Institutional ethics approval was obtained from the Department of Sport, Health and Exercise Science Research Ethics Committee at the University of Hull (REF – FHS230), with additional ethical considerations described in Chapter 3. Participants in this study were invited to take part in the semi-structured interviews but this was not mandatory and written consent was obtained separately.

8.2.2 Research team and reflexivity

All interviews were conducted by the lead investigator AW, male, PhD student who had no prior interview experience. A relationship with participants was established during other laboratory trials performed prior to the semi-structured interviews. Participants were aware the semi-structured interviews were being conducted as part of a PhD and were aware of the aim of the study. The interviewer's philosophical paradigm is described in Chapter 3.

8.2.3 Participants

Participants represented a sub-sample of people who were originally recruited from the quantitative study (described in Chapters 5 and 6). Participants were interviewed directly after completing the final overground trial on their third visit to the laboratory. Interviews were completed in the laboratory where the participant and lead investigator were the only people present. Interviews were completed on campus at the University of Hull. Participants (Table 8.1) were 43.5% female, aged 18-65 (mean [SD] 31 ± 11 years). Participants were made aware that their interview would be recorded, but data would remain anonymous.

Table 8.1 Participant's age, sex, and occupation.

Participant	Sex	Age (years)	Occupation	Maximal oxygen consumption ($mL \cdot kg^{-1} \cdot min^{-1}$)
1	M	32	Operations manager	58
2	F	28	Lab technician	36
3	M	32	Energy surveyor	62
4	M	28	Crane driver	57
5	F	41	Medical doctor	47
6	M	40	General Practitioner	52
7	M	24	Student (Sport Science)	42
8	F	29	University lecturer (Sports Therapy)	51
9	M	28	Lab technician	52
10	F	58	Finance assistant	23
11	M	26	Teacher	53
12	F	28	Student (Sport Science)	33
13	F	55	Medical doctor and anaesthetist	28
14	M	49	Professor of Teaching	34
15	F	23	Student (Biology)	53
16	F	24	PhD student (Computer Science)	19
17	F	29	Lecturer (Sports Therapy)	48

18	M	20	Student (Sports Coaching)	44
19	M	18	Student (Languages)	45
20	F	40	Researcher (Cancer)	33
21	M	21	Computer science student	45
22	M	24	PhD student (Geoscience)	34
23	M	19	Jeweller	58

8.2.4 Data collection

Participants were invited to complete a one-to-one interview with the lead investigator. The semi-structured interview guide (Appendix F) accommodated assessing individual responses and comments while enabling the identification of shared themes across participant answers. A combination of open (n=12) and closed (n=9) questions were used for each interview, as the structure of the interview was not limited to the guide, it allowed for additional questioning to gain further insight and clarity when required. The semi-structured interview was initially pilot tested. No repeat interviews were conducted.

The purpose of the core questions centred around obtaining a retrospective assessment of participants' perceptions of nudges to promote physical activity via wearable technology. Specifically, there was direct questioning based on the physical trials performed in the laboratory on the same day to obtain participants' perception of 3 key areas: 1) Perceptions of the metronome and haptic cues to guide walking pace, 2) perceptions of walking speeds during the 3 walking conditions described in Chapter 7 (the self-paced walking trial, the metronome guided walking trial and the haptic cue guided walking trial), and 3) perception of wearable technology, and their preferences for its use outside of a laboratory setting. The interviews lasted approximately 10-15 minutes, were audio-recorded and transcribed verbatim, and participants were not identified in the recordings or in the transcripts. Five participants were selected for member checking, to check for clarity and accuracy of transcription.

8.2.5 Data Analysis

To understand individual perceptions of wearable technology and nudge theory to guide physical activity, the text was analysed using a thematic analysis, based on a 6 stage-process, because of its flexibility and potential to deliver rich and complex understandings (Braun and Clarke, 2006). A deductive semantic approach to the data coding was used, with data analysed within the explicit or surface meaning of the data. Responses were explored by the lead investigator AW, involving the following six steps: (1) familiarisation with data, (2), initial coding, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing the report.

8.3 Results

The findings and main themes are described below.

8.3.1 Theme 1. Benefits of cadence cues

Participants were asked, "if the cadence cue had the ability to improve CV health by guiding them to the correct intensity would they be more inclined to use it?" 19 of 23 participants confirmed they would use cadence cues if it had the ability to improve their CV health.

'Probably, but I would also probably not use it if I was walking around traffic because I would end up concentrating on that instead of what I was doing.' (participant 2, **aged** 28)

'*I suppose yes but I guess realistically I do plenty of exercise so adding something else in. I don't feel like I would necessarily need to do it, but obviously because my walking speed was variable, maybe it would be useful for me too*' (participant 5, **aged** 41)

'*I would yeah but it would change the purpose of the walk for me, like if I was doing it optimally, I'd obviously be walking around at quite quick speed like I was [in the lab/study], whereas when I go for a walk it's more kind of, I'm gonna go and have a look what's about and chill out'* (participant 012, **aged** 24)

'I think that I think it's super useful. Yeah, I think that having a pacing cue would be very useful for a lot of people because they wouldn't have to guess what is warm enough or what is breathless enough [referring to NHS physical activity guidelines] that kind of thing' (participant 20, **aged** 40)

When those participants who said they wouldn't use the guidance cues (4 of 23 participants) were asked for a reason why they would not use them, regardless of CV benefit, they referred to the other forms of physical activity they completed, and their belief that this was adequate enough without additional walking, or the perception that there were no benefits from wearable nudges.

'It's just something I'm not that I'm interested in, not that bothered' (participant 12, **aged** 28)

'I just think I do enough anyway I don't need the extra physical activity' (participant 15, **aged** 23)

'Motivation should be from the mind, not from a wearable. Honestly, I'm old fashioned' (participant 13, **aged** 55)

8.3.2 Theme 2. Uncertainty in a real-world setting

When participants were asked if they would use the metronome cue when walking outside, there was a theme of uncertainty regarding its usability in a real-world setting:

> *'No, I nearly fell so many times [in the lab]. I would also probably not use it if I was walking around traffic because I would end up concentrating on that instead of what I was doing.'* (participant 2, **aged** 28)
>
> '*I would use a sound, yeah if it was a sound on a watch, yeah definitely'* (participant 10, **aged** 58)
>
> *'I might use the audio one yeah, I think it's useful. Particularly at the start. I suppose the other thing is once you know what speed you should be doing. Then it's whether it adds any value after that, I'm not sure, so I might do.'* (participant 14, **aged** 49)
>
> *'No, I don't think I need to, I don't walk for exercise. I just walk to get places, I do enough physical activity anyway, so I don't feel as though I need to use it'* (participant 15, **aged** 23)
>
> *'No, probably because I just walk at the pace that I wanna walk at, so I don't feel the need to be hitting something*' (participant 17, **aged** 29)

Useful as a training tool

Another subtheme that arose from participants' perception of the metronome cue was that of a purposeful training session or walk, whereby in a certain context they felt the metronome cue would be useful.

> *'I think if I was going out for a walk or hike, that was part of my training plan where I needed to keep up as specific amount of intensity throughout then, yeah.'* (participant 3, **aged** 32)
> *'Uh, I thought I was more, I was more accurate with that so If I was aiming for something a specific measurable outcome then I probably would'* (participant 5, **aged** 41)

8.3.3 Theme 3. Drawbacks of wearables for cadence cueing

A clear theme that arose from the use of the cadence cues was around drawbacks associated with the technology, such as disconnection after a certain period and irritation with the cues.

> *'Like if you were listening to that for a long period of time you would just switch off from it.'* (participant 4, **aged** 28)
> *'It's, it's, it's quite intrusive and quite annoying, I think I would yeah if you could calibrate yourself for 10-15 seconds periodically. If you felt you needed to do that, but longer than that, it would drive you mad.'* (participant 6, **aged** 40)
> *'Just listening to that for however long you need to walk for I think would be quite monotonous'* (participant 012, **aged** 24)

'If it had an on off function that we could use sporadically I'd be more inclined to use it' (participant 14, **aged** 49)

'The noise gets kind of irritating after a while' (participant 18, **aged** 20)

'Because one, I think it would annoy me and two because I think my self-paced walking tends to be sufficient enough' (participant 23, **aged** 19)

Additionally, participants reported feeling irritated by the changes in speed, which depended on whether they were meeting the required moderate intensity %HRR thresholds when walking in the lab.

'If I was trying to obtain a certain pace, it would be very useful and is if it wasn't so up and down. If it changed less [it would be useful]' (participant 20, **aged** 40)

'The pace [of the cue] was a bit too quick, so during the [laboratory] trials I tried shortening my stride to match it and then it became uncomfortable' (participant 22, **aged** 24)

'It's all abrupt, walking fast, then walking slower than walking quick again. This change in speed [that the app administers depending on heart rate] is a bit annoying' (participant 16 **aged** 24, 2 **aged** 4)[participant referring to the change in cadence cue administered by the app depending on boundaries set at 40 – 45 %HRR, i.e., if the participants %HRR was above 45% the cadence cue would slow down, if it was below 45% it would speed up]

8.3.4 Theme 4. Methods of cadence cueing

When participants highlighted potential drawbacks with the metronome and haptic cadence cues, participants were asked to reflect on how cadence cueing via other methods may be more suitable. A subtheme of music use when walking was apparent that several participants highlighted:

> ‘*I tend to use headphones [to listen to music] when walking* ‘(participant 4, **aged** 28)
>
> ‘*You see, I don't think I would [use the metronome cue when walking outside], because if I walk on my own, I'd listen to music’* (participant 012, **aged** 24)
>
> *‘Normally it's sort of walking to get somewhere. I'm just kind of listening to music. I have more focus on music’* (participant 18, **aged** 20)
>
> *‘Usually, I have music playing when I walk’* (participant 19, **aged** 18)
>
> *‘If the metronome was replaced by music, I’d be more likely to use it’* (participant 21, **aged** 21)
>
> *‘But yes, my pace does change based on what I'm thinking of, and especially for listening to music’* (participant 21, **aged** 21)
>
> *‘Usually whenever I walk anywhere, I have headphones in listening to music’* (participant 23, **aged** 19)

Haptic strength

When participants were asked about their perception of the haptic cues, a key issue related to the strength of the haptic feedback, which many felt was insufficient to guide their walking pace effectively.

> *‘If I could feel [the haptic cue] more prominently then I’d be more incline to use it’* (participant 2, **aged** 28)
>
> *‘No, cause I found it difficult to keep in time to’* (participant 1, **aged** 32)

'Uhm, I didn't find that as easy to use, I wouldn't choose it. It was more difficult to feel if I was in the right, on the right rhythm' (participant 5, **aged** 41)

'If it was stronger then I'd be more incline to use it' (participant 6, **aged** 40)

'I found that very difficult, Just the I suppose the buzzer strength or the the vibration strength when I put my arm down by my side and I was trying to concentrate on that and the arm was swinging It was very difficult whereas I had to like put a finger on the watch' (participant 012, **aged** 24)

'The hearing one [metronome] was easier to use then the haptic cue' (participant 8, **aged** 29)

'…but not the haptics no, no. I found it quite difficult to follow' (participant 10, **aged** 58)

'Couldn't feel the vibration it wasn't strong enough' (participant 11, **aged** 26)

'But the feeling of it just felt the same as when you can feel your pulse after you've run' (participant 12, **aged** 28)

'I mean it [Apple Watch] has to be tight enough to be able to feel it' (participant 20, **aged** 40)

There was no deviation from the pre-registration.

8.4 Discussion

This study investigated participants' perceptions of guiding physical activity via digital nudges through wearable devices. The participants in this qualitative study included both males and females, and across a broad age range and demographics. Several main themes were identified.

8.4.1 Theme 1. Benefits of cadence cues

Theme 1. Benefits of cadence cues revealed most participants would use wearable devices and nudges if it guided them to perform physical activity that would benefit CV fitness. While these findings seem positive, an awareness of the need to perform physical activity has been well documented (Brown et al., 2022; nhs.uk, 2022), and even though people might not be able to recall specific guidelines, an awareness that physical activity improves health is well accepted in the public domain (Plotnikoff et al., 2011; Knox et al., 2015; Vaara et al., 2019). However, it is clear, at a population level, people still find it difficult to engage in health promoting behaviours such as exercise (Guthold et al., 2018).

8.4.2 Theme 2. Uncertainty in a real-world setting

A key theme that arose from the use of metronome cue was Theme 2, 'Uncertainty in a real-world setting'. Participants expressed hesitancy to use the metronome cue outside for several reasons, including awareness around traffic and increased risk of falling. One's environment can have a significant impact on walking speed and cadence including urban infrastructure such as pedestrian crossings, and pedestrian facilities (Bosina and Weidmann, 2017). Walking speed can also be influenced by environment with people tending to walk faster in urban areas without greenery and with more traffic and pedestrians, compared to sections with less traffic and more greenery (Franěk, 2013). This may impact the usability of a cadence cue in urban areas to guide users to a certain walking speed as infrastructure often dictates walking speed (Rastogi, Ilango and Chandra, 2011), as highlighted by participants' views in this study. Research into cadence cueing in a community or urban setting is warranted. Some evidence on cadence cueing currently exists, but these studies were conducted within a laboratory setting (Rowe et al., 2013; Wittwer, Webster and Hill, 2013; Ducharme et al., 2018). The application of cadence cueing in a real-world setting, where pedestrians interact with several variables has not been investigated and warrants further exploration.

Additionally, one participant (participant 2) raised concerns of the metronome cue causing a distraction that may impact safety when walking among urban areas with greater amounts of traffic. Lichenstein, Smith, Ambrose, & Moody, (2012) completed a retrospective investigation into pedestrian injury and death in the United States. Of the 116 reported pedestrian injuries and deaths during 2004 – 2011, 74% of cases reported victims were wearing headphones at the time of the incident. This may explain participants' apprehension in using an audio cue when walking continuously in areas of dense traffic and may point toward the haptic cue as a safer method for guiding walking cadence under these conditions.

Another area of concern for its applicability in the real world was the risk associated with walking speed and falling. As part of the current research, the cadence cue often set a quick pace, with participants in the laboratory studies averaging 129 ± 14 steps·min^{-1} when guided via the metronome cue. In elderly (78 [5] years old) populations a U-shaped relationship between gait speed and falls exists, as slower and faster speeds are associated with a greater risk of falling, and a faster speed is associated with an increased risk of outdoor falls (Quach et al., 2011). However, this apprehension may not be warranted in free living walking where a reduction in falls is associated with increased cadence. For every 10 steps·min^{-1} increase in cadence, there is an associated 13.2% reduction fall rate (Urbanek et al., 2022). Additionally, Urbanek et al. (2022) reported among higher functioning participants that every 10 steps·min^{-1} above 100 steps·min^{-1} was associated with a 27.7% risk reduction in falls. Based on these findings, the apprehension of falling at a greater walking cadence highlighted in the current study may not be warranted and a faster walking cadence above 100 steps·min^{-1} may help in reducing falls.

8.4.3 Theme 3. Drawbacks of wearables for cadence cueing

Another theme from the metronome cue was 'drawbacks.' Several participants highlighted they found the metronome cue to be irritating, while others expressed a disconnection from the cue after a certain period of time. Metronomes have been used as a guidance tool with success in a range of activities including walking (Rowe et al., 2013; Wittwer, Webster and Hill, 2013) and music instrument playing (Fujii et al., 2011). However, to the best of the author's knowledge, its application as a training device used intermittently to guide walking speed has not been investigated. Therefore, it is unclear how much time is required walking with a guidance cue before participants habitually walk fast enough to reach moderate intensity. Karuei and MacLean (2014) investigated the use of haptic notifiers placed on participants' wrists as a method of guiding walking cadence. Participants were exposed to a single 20-second haptic cue and then instructed to walk for 40 seconds replicating the same speed. Those authors reported that participants succesfully replicated their walking cadence with a 5% error after a single practice trial. Whether this would have translated into longer habituation is unclear, as attentional focus is unlikely to be impacted during a 40 s trial (Neumann, 2019) in the same way walking for a sustained period would be.

While there may be a level of tedium listening to a continual metronome, there may be more ethical concerns from participants and their perceptions of the nudge guidance inhibiting autonomy. Wearable devices offer the opportunity to improve health outcomes, and encourage physical activity by stimulating choice architecture (Thaler, Sunstein and Balz, 2012). There is however, a theory that nudging may clash with central moral values like liberty and autonomy, inhibiting individuals' free choice (Schmidt and Engelen, 2020). One participant (participant 17 **aged** 29) referred to not using the cadence cues as they wanted to walk at their own pace and did not feel the need to meet the demand of the auditory cue. Another participant (participant 15 **aged** 23) also stated their perception of performing enough physical activity away from walking, which swayed their opinion in using the cadence cues. This object awareness and lack of desire to engage with the cadence cueing agrees with previous findings whereby participants engaged in a sense-making process, actively reinterpreting the relevance of nudges and assessing the prescribed action in the context of their everyday life (Toner, Allen-Collinson and Jones, 2022). People essentially interpret the nudges and make an individualised, informed decision based on other external and internal factors, as opposed to feeling the necessity to engage immediately.

Several participants highlighted they would be more inclined to use the cadence cue if it had the ability to turn off, such as synchronising walking speed initially, becoming accustomed to the speed, and then having the option to turn off the cadence cue. Using a wearable cadence cue as a training device aligns with the 'Internet of Things' concept for healthful behaviour change (Nakamura, 2021). The author identified three key functionalities between wearable devices and human interaction. First, the device tracks the user's lifestyle habits, in this case the device tracks walking speed and heart rate and predicts a walking cadence that will allow the user to reach 40% HRR. Second, the user's actions are recorded on the device, with pictures, numbers, graphs etc, reported by the wearable device; and finally, the device delivers real-time feedback to the user to reflect on their behaviour to encourage self-reflection. The use of nudges aims to increase healthy behaviours and reduce unhealthy actions (Nakamura, 2021). This may reflect why participants in this study suggested the cadence cue should have an ON - OFF mechanism whereby it could be used as a training tool rather than persistent nudges, raising awareness of the correct walking speed and teaching self-awareness which then promotes long term habit formation. For this research, it is about encouraging a walking speed suitable to elicit cardiovascular benefit.

8.4.4 Theme 4. Methods of cadence cues

Another common theme among participants was 'music use'. Several participants highlighted they preferred to listen to music while walking, as opposed to using a metronome cue. Music use during physical activity has been linked with several benefits. During endurance performance, motivational and stimulative music has been shown to enhance performance, reduce perceived exertion, improve energy efficiency, and increase work output (Karageorghis and Priest, 2012). Music also has synchronous ability whereby exercise can be guided via music tempo and speed. Karageorghis & Priest (2012) reported a rhythm response referring to "an innate human predisposition to synchronise movement with musical rhythms" (Karageorghis and Priest, 2012 p49). Humans' ability to synchronise movement with music is thought to be a neuropsychological tendency that occurs between movement frequency and music tempo that reflects electroencephalographic delta frequency activity in the brain (Schneider et al., 2010). The process is thought to coordinate incoming afferent nerve signals with their efferent counterparts that direct muscle activity (Karageorghis and Priest, 2012). This may be of benefit to participants as they subconsciously synchronise their walking pace with the music tempo, without the use of a metronome, or what some may deem as unnecessary nudges.

One participant (participant 21 **aged** 21) highlighted that their own walking pace was dictated by the music they listened too, which may correspond to the type of music and sonic characteristics (sound waves, resonance, and energy) influencing walking speed as opposed to synchronisation between music tempo and walking cadence. There are implications for walking synchronisation and music as the musical characteristics (e.g., tempo, key, instrumentation, genre, arrangement) play an influential role that may make it more difficult to attenuate a given walking intensity (Wittwer, Webster and Hill, 2013). Music (depending on genre) has the ability to impact mood, behaviour, tension, and mental clarity (McCraty et al., 1998; Ahmad and Rana, 2015). Franěk, van Noorden, & Režný, (2014) investigated walking speed and different music tempos in an urban setting. Music beat as well as the sonic characteristics all influenced walking speed but did not lead to precise synchronisation. These authors reported some participants to partially synchronise steps with beats·min^{-1} while others lacked ability to synchronise steps with the music completely. However, the authors did not report how the synchronisation between music tempo and cadence was analysed. The authors also reported that fast energetic music (dance music with clear and strong percussive often electronic accompaniment) increased walking speed, while slow music (music that consisted of ballads and sing-a-song style mood music) slowed the walking tempo. The concept of music dictating walking speed was highlighted in the current study by participant 21 **aged** 21. Moumdjian et al., (2019) investigated music and metronome cadence cueing when walking in 28 healthy participants and 27 participants with multiple sclerosis. Participants performed 12-minute trials with an individualised optimal tempo generated using a D-jogger, an adaptive music player consisting of software, headphones, and two wireless inertial measurement units strapped at the ankles for measuring cadence and step times (Moumdjian et al., 2019). The software had the ability to match music speeds with individualised walking tempo. During the music trials, both healthy controls and participants with multiple sclerosis walked faster with music compared to control trials. Furthermore, synchronisation with music was better than with a metronome, although synchronisation with music waivered in the final 3 minutes of the 12-minute trial and was closest during minutes 3 – 6. Results indicated that all participants anticipated the beats, evidencing auditory-motor coupling (i.e., the participants aligned their steps with the beat according to a temporal prediction model that minimises the timing error between steps and music beat). However, mean cadence (steps·min^{-1}) and mean music beats·min^{-1} for walking trials were not reported. Additionally, the software they used had the capacity to match walking speed with music beats between 80-130 beats·min^{-1}, as the technology has the capacity to match music tempo with walking cadence. However, it is unclear whether participants aligned walking speed to the beat of the music or whether the software adapted music tempo to match walking speed. Synchronisation between walking cadence and music tempo may have a walking speed 'sweet spot' where synchronisation between music tempo and walking cadence are most closely synchronised. An optimal cadence of 120 beats·min^{-1} but with a range of 106 – 130 beats·min^{-1} may elicit the highest rate of synchronisation (Styns et al., 2007). The mean cadence at 40% HRR was 123 (120 – 126) steps·min^{-1} as highlighted in Chapter 5, which aligns closely with the 'optimal' beat frequency mentioned above. However, while this range may produce a high level of synchronisation it may not be suitable for all people to obtain moderate intensity, as highlighted by the range of cadences required to reach criterion moderate intensity (40% HRR) in Chapter 5

Additionally, there may be a link between heart rate and music tempo, with slower tempos (50-60 beats·min^{-1}) associated with a reduction in blood pressure and heart rate, while those with a faster tempo (120-130 beats·min^{-1}) stimulate physiological responses such as increased blood pressure and heart rate (Armon et al., 2011; Bora, Krishna and Phukan, 2017). As the purpose of this investigation was to elicit a heart rate response associated with moderate intensity (40% HRR), using different types of music may enhance participants' physiological responses to reach these thresholds, enhancing the benefit of physical activity. Music use during low and moderate intensity exercise has also been associated with a reduction in RPE (Szmedra and Bacharach, 1998; Potteiger, Schroeder and Goff, 2000) which has the potential to increase exercise adherence (Parfitt, Olds and Eston, 2015).

Synchronisation of walking cadence to music tempo has already been investigated, but its ability to direct participants to an intensity that will elicit cardiovascular benefit has yet to be explored. There are several associated negatives to using music to guide walking intensity, not least, the safety risks highlighted above, regarding pedestrian accidents involving headphones (Lichenstein et al., 2012). Never-the-less, several participants from this study highlighted their enjoyment for listening to music while walking, therefore, additional research into music tempo and walking cadence synchronisation at a speed deemed to meet CV benefit warrants further investigation.

The final subtheme outlined from participants was ‘haptic strength’. Participants perceived the haptic feedback strength on the Apple Watch to be too weak to accurately synchronise to their walking cadence. There is very little research on haptic feedback as a guide to walking synchronisation. However, its benefits for use in a public setting are easy to outline, as there is a reduced risk of distraction that headphones may cause (Lichenstein et al., 2012), and a less invasive form of guidance, compared to metronome cues. Previous research has used haptic feedback to guide walking performed on a treadmill with sensory feedback provided through the foot (Maculewicz, Erkut and Serafin, 2016). In Maculewicz et al’s (2016) study, participants perceived haptic feedback to be significantly more difficult to synchronise with, compared to sound. While participants reported difficulty in synchronising haptic cues with walking cadence in the current study because the perception of haptics was weak, there may be evidence to suggest a delayed response to touch, compared to sound, exists. Reaction to sound ranges from 140 – 160 $m \cdot s^{-1}$ in healthy adults, compared to 155 $m \cdot s^{-1}$ to the sense of touch (Kosinski, 2008). This slightly delayed response to touch compared to sound may also affect participants’ ability to synchronise cadence with haptic feedback. Yet the real-world application of haptic guidance offers a more discrete and less invasive interaction between wearable and user. Haptic impulses are dictated by the manufacturer, and a trade-off between sleek design and size of the haptic engine exists in the Apple Watch design. Additionally, the current application programming interface (API) for the Apple Watch haptic engine is designed for one off nudge notifications that are not designed to be played continually for 10 minutes. As the MVPA app in this study was designed to push the boundaries of the Apple Watch device, and incorporate continual nudges for a sustained duration, the Apple Watch haptics were not designed for this purpose, which limited the strength of the haptic cue available. Nevertheless, the use of haptic feedback to guide walking intensity is a promising feature and further investigation of the applicability of stronger haptic impulses to guide walking cadence warrants research.

8.5 Conclusion

The purpose of this study was to outline participants' perceptions of digital nudges and its applicability in wearable devices to promote physical activity. While participants seemed open to the use of nudge theory via wearables if it had the capacity to improve CV health, it was clear participants felt the metronome sound was irritating and that haptic feedback strength was insufficient to guide walking accurately. Music use is enjoyable in physical activity and has several benefits. Wearable technology offers a heightened opportunity to aid physical activity adherence and guidance, enhanced by its proximity to the human body. Participants in this study were open to the use of wearable technology and nudge theory to promote physical activity.

9. General Discussion, Conclusions, Limitations, Future Research, Recommendations, and Practical Applications.

This final chapter is intended to summarise the primary aims and findings of the thesis from both quantitative and qualitative chapters. This chapter will also identify the practical application of the findings and highlight potential future research recommendations. The thesis used a blend of experimental trials, observational trials, systematic review with meta regression, and semi-structured interviews to achieve the aims of the thesis, which were:

1. Examine the agreement and relationship between %HRR and METs.
2. Examine how well %HRR as measured by the Apple Watch compares to criterion intensity (VO_2R) and the native Apple Watch Activity app for measuring moderate intensity while walking.
3. Examine the plausibility of guiding walking cadence to meet relative moderate intensity via metronome and haptic feedback from the Apple Watch.
4. Examine the perceptions of participants surrounding the use and knowledge of moderate intensity and physical activity guidelines.
5. Examine the perceptions of participants on wearable technology.

9.1 General Discussion

The purpose of this thesis was to examine the individualisation of physical activity measurements, with a specific focus on the implementation of wearable technology. It is therefore of significant importance to identify a measure of physical activity intensity that is both accurate, allows for individualisation of physical activity intensity, and can be implemented on a large scale, across the population with the use of wearables. Longer term, it is hoped that this thesis will aid in the justification for the use of relative measures of physical activity in both wearable devices and in health promotion material and government guidelines for physical activity. Specifically, it is hoped that the use of wearable devices can be implemented as a means of prescribing and measuring physical activity to the public. This would allow a larger percentage of the population to adopt individualised relative physical activity monitoring and prescription, as opposed to using absolute values that are not specific to an individual's cardiorespiratory health. The overarching aim of individualising physical activity intensity is to promote more specific physical activity that is of greater benefit to the population and theoretically should optimise physical activity for the individual's cardiorespiratory health. Ideally, it is hoped that individualisation of exercise intensity could improve the general cardiorespiratory health of the population and potentially reduce associated co-morbidities (Freitas et al., 2018; Park et al., 2020).

Current government guidelines for physical activity and most wearable technology, monitors physical activity via absolute methods such as METs (based on triaxial accelerometer data). METs were first standardised in the late 80's and have been used ever since to quantify exercise intensity (Jetté, Sidney and Blümchen, 1990). METs are defined as the amount of oxygen consumed during seated rest and is equal to a standardised value of 3.5 $mL \cdot kg \cdot min^{-1}$. The applicability of METs across the spectrum of the population and exercise modalities has seen significant growth in its popularity as a means of measuring and prescribing exercise intensity. Three METs are associated with moderate intensity physical activity (Liguori, 2022). However, there is evidence to suggest the validity of METs to prescribe exercise intensity on an individualised basis is unfounded (Byrne et al., 2005). Considering this, Chapter 4 sought to quantify the discrepancies between relatively measured compared to absolutely measured (METs) physical activity. By performing a meta-regression from three study's raw data (Dos Anjos et al., 2011; Gil-Rey et al., 2019a; Sweegers et al., 2020) this chapter was able to provide strong evidence to highlight the discrepancies in physical activity intensity variables, specifically the differences between METs and %HRR. This has important implications for real world application of physical activity intensity monitoring and prescription. A number of authors have sought to provide physical activity guidelines based on the premise that three METs equates to moderate intensity (Tudor-Locke et al., 2011; Harrington et al., 2012; Aguiar et al., 2019), while others have published findings to contradict using this variable to quantify physical activity intensity (Serrano et al., 2017; O'Brien et al., 2018; Abt et al., 2019).

The results from Chapter 4 clearly identify that there are large discrepancies between relative and absolute physical activity intensity variables. The meta regression modelled from raw data from previous studies (Dos Anjos et al., 2011; Gil-Rey et al., 2019a; Sweegers et al., 2020) indicated that at three METs %HRR was approximately 32%, significantly under the 40% HRR threshold for relative moderate intensity. Additionally, agreement between relative and absolute measures of intensity when comparing raw data was 43%, i.e., if absolute intensity was moderate (3-5.99 METs) and %HRR was 40 – 59%, then this would be classified as agreement between the two variables. However, if METs were recorded as moderate intensity (3-5.99 METS) and %HRR was light intensity (<40%HRR) then this would be classified as a disagreement. It is therefore likely that current absolute guidelines for physical activity are underestimating the intensity required to reach relative moderate intensity for large sections of the population. The benefit in using relative measures is that cardiorespiratory markers such as HRmax and HRrest are taken into consideration to calculate intensity thresholds. Resting heart rate is a good indicator of cardiovascular health (Jensen et al., 2012; 2013; Kang, Ha and Ko, 2017) and thus, a personalised approach to physical activity intensity should incorporate this measure. The findings from this chapter are fundamental for the remaining chapters of this thesis and lay the foundation for the experimental trials. The remaining experimental trials sought to evidence the applicability of relative physical activity intensity, in walking, via wearable technology in a bid to improve the validity of monitoring and prescribing physical activity intensity.

The smart watch is the fastest selling wearable device (Statista, 2023) and the Apple Watch is the most popular smart watch (Statista, 2023). Currently, when the Apple Watch is recording 'exercise' on the green 'exercise' ring (and when not in a specific 'workout' mode), the Watch is recording physical activity via absolute intensity variables. Chapter 5 sought to investigate the accuracy of the Apple Watch exercise ring and the use of a relative measure (%HRR) taken using the photoplethysmography (PPG) sensor in the Apple Watch, via a bespoke app (MVPA app), against a laboratory standard measure of heart rate (Polar chest strap) and a criterion measure of exercise intensity, %VO_2R. While the chapter examined the accuracy of the Apple Watch for measuring physical activity, it also sought to investigate the useability of subjective measures including RPE, thermal sensation, breathlessness, and a talk test as a means of subjectively monitoring physical activity intensity, specifically, how well people can identify moderate intensity from these subjective measures.

The results from Chapter 5 indicate that the Apple Watch exercise ring overestimates physical activity during walking when compared to criterion moderate intensity (40% VO_2R). The Apple Watch native app recorded 'exercise' at a mean (SD) 33 (10) % VO_2R, compared to the MVPA app which recorded moderate intensity physical activity at 43 (9) %VO_2R. Additionally, when compared to the chest strap %HRR the Apple Watch again overestimated physical activity recording 'exercise' at 33 (10)% HRR, while the MVPA app recorded moderate physical activity at 44 (3)% HRR. First, the results indicate that the Apple Watch exercise ring overestimates moderate intensity physical activity, while the MVPA app nearly always ensured the participant was performing relative moderate intensity physical activity. These findings are similar to those previously reported, indicating the Apple Watch overestimates moderate intensity 'exercise' (Abt et al., 2019). However, the findings from the MVPA app are novel, in that an Apple Watch has the capability to accurately monitor relative moderate intensity physical activity via %HRR when compared to criterion measures of MPA (ECG chest strap %HRR and %VO_2R). The walking cadence required to elicit moderate intensity was also modelled in a regression analysis. The cadence required to reach criterion moderate intensity was ~125 steps·min^{-1}, which is substantially higher than the previously reported 100 steps·min^{-1} (Tudor-Locke et al., 2011; 2018; Aguiar et al., 2019). Moreover, at 3 METs the lower bound of absolute moderate intensity, mean (SD) %HRR, %VO_2R, and cadence were 25% (8), 23% (8), and 103 steps·min^{-1}, respectively. The criterion %VO_2R indicates a walking cadence of 100 steps·min^{-1} largely underestimates the walking cadence required to reach relative moderate intensity and indicates a need to individualise exercise guidance to ensure people are exercising at an appropriate intensity to optimise health benefits. Currently, when using absolute physical activity intensity thresholds, it is likely a large percentage of the population are not performing physical activity with adequate intensity to ensure that they meet the physical activity guidelines optimise their health.

Resting heart rate was also quantified using three different methods. When compared to the criterion 30-minute supine recorded RHR protocol, the 5-minute protocol embedded in the MVPA app overestimated mean RHR ~1 beats·min^{-1} while the 7-day Apple Watch underestimated RHR by ~3 beats·min^{-1}. While it is unlikely wearable device users would be willing to maintain a supine position for 30-minutes or 5-minutes while heart rate is recorded, the magnitude of difference in real-world applicability may be negligible. For example 40% HRR for a 30 year old, with a resting heart rate of 50 beats·min^{-1} (using the Gellish et al. (2007) formula) would equate to a lower bound for moderate intensity of 105 beats·min^{-1}. In comparison, a RHR of 53 beats·min^{-1} would equate to a lower bound for moderate intensity of 107 beats·min^{-1}, a difference of 2 beats·min^{-1}. It is likely that the trade-off between using historically stored data, whereby wearable device users do not have to perform additional RHR protocols to quantify physical activity, outweighs the potentially more accurate physical activity intensity boundaries collected using discrete protocols. The use of background RHR as recorded automatically by the Apple Watch might represent a 'sweet spot' between convenience and accuracy.

Maximal heart rate was also quantified using 3 different methods. The Gellish et al. (2007) formula was the most accurate at predicting HR_{max} when compared to the criterion measured during a maximal oxygen consumption test (~ 1 beats·min^{-1} difference). However, the popular formula 220-age overestimated HR_{max} by ~ 4 beats·min^{-1} compared to the criterion measure. Based on these findings wearable device manufacturers should consider using the Gellish et al. (2007) formula to quantify HR_{max} more accurately, if they aren't already doing so.

The chapter also highlighted the effectiveness of subjective measures for identifying moderate intensity. RPE and breathlessness scales were the most useful subjective identifiers of moderate intensity, both somewhat identifying ‘moderate’ exertion and breathlessness close to 40 %HRR. However, the variability in the subjective measures reported indicate that it is not an adequate replacement for objectively measured relative intensity physical activity monitoring. For example, the 95% credible intervals spanned from 23% to 57% HRR at an RPE of 3 and 25% to 60% HRR at 8 on the breathlessness scale. Thermal sensation overestimated moderate intensity, and the talk test was poor at identifying moderate intensity physical activity. As a result of these findings, National Health Services (nhs.uk, 2022) may wish to consider the usefulness of subjective guidance, especially those subjective intrinsic feelings of ‘feeling warmer, breathing faster, and being able to talk but not sing.’

Considering these findings, practitioners and wearable device manufacturers may wish to reflect on the implications of using absolute physical activity intensity variables to quantify physical activity. Consequently, it is likely that wearable devices are overestimating physical activity completion. This has real world implications, as wearable technology has the ability to improve physical activity participation through goal setting, gamification, and sustainable lifestyle modification (Bajpai et al., 2015; James, Deane and Wallace, 2019; Cho, Kaplanidou and Sato, 2021). However, if the wearable device is not accurately quantifying physical activity, it may be misleading consumers. While people may perceive that they are achieving physical activity duration, dose, and intensity guidelines, it is likely that they are not performing physical activity at an intensity (moderate) associated with cardio-respiratory benefits (Swain, 2005; Brown, Harhay and Harhay, 2014), and as such a shift towards using relative measures to record physical activity completion is required by wearable device manufacturers.

Considering the inaccuracies in walking cadence required to meet absolute moderate intensity, Chapter 6 sought to implement the use of the Apple Watch to guide users to relative, moderate intensity via cadence cueing. While other authors have sought to investigate the use of metronome (Dickstein and Plax, 2012; Wittwer, Webster and Hill, 2013) and haptic cues (Lylykangas et al., 2013; Karuei and MacLean, 2014) to guide walking cadence, with success, trials were performed over a short walking distance (often 10 m) and not for a sustained period of time. Additionally, the cadence cue was set to pre-determined speeds (i.e., 90, 100, 100, 110 steps·min^{-1}) or matched to replicate participants' normal walking speed. In the current study the cadence cue was designed to guide users to criterion 40% HRR and keep them within the lower and upper bound of 40 – 45% HRR. This meant the cadence cue had the ability to change tempo during trials, which meant participants had to modify their cadence during trials to synchronise with the cadence cue. Trials were performed for 10 minutes on a ~60 m figure-of-8 track to somewhat replicate walking outside, where people do not typically walk in straight lines. Finally, to implement a device that could theoretically be used in 'real-world' walking, the metronome cue was administered to participants via the Apple Watch through Bluetooth headphones, and haptic cues were delivered via the Watch's haptic engine. These trials were compared to a self-paced trial whereby participants were instructed to walk at NHS guided moderate intensity (nhs.uk, 2022).

The results from Chapter 6 indicate that synchronisation with the metronome cue was poor. Synchronisation between the metronome cue and foot contact occurred in 43% of foot contacts. Synchronisation was achieved if foot contact was made within -0.1 to 0.1 seconds of any metronome tick. These results contradict previous findings (Dickstein and Plax, 2012; Wittwer, Webster and Hill, 2013), but as previously discussed this is likely due to the duration and design of the trials being performed. The metronome did have the capacity to guide participants to criterion moderate intensity with some success, guiding 81% of participants to criterion moderate intensity during the 10-minute trial of overground walking.

The haptic cue's ability to guide users to a cadence that elicited moderate intensity physical activity was less successful compared with the metronome (68% of participants were exercising at criterion moderate intensity during haptic trials). However, the haptic cue outperformed the self-paced government guideline walking trials, where 50% of participants reached criterion moderate intensity when instructed to walk via NHS guidelines (nhs.uk, 2022). Reasons for the indifferent performance of the haptic cue is likely due to the strength of the haptics as highlighted in Chapter 8, with participants finding the strength of the haptic cue to be too weak to feel during walking trials with a natural arm swing.

As evidenced in Chapter 6, people's ability to interpret physical activity guidelines and complete physical activity at an adequate intensity to meet the demands of moderate intensity, is subjective and interpretational. It is, therefore, important to understand how physical activity guidelines are interpreted by the general population. By completing semi-structured interviews, we were able to gain insight and a better understanding of how participants in this study interpreted the NHS guidelines for moderate intensity physical activity (nhs.uk, 2022) that they were guided by in the self-paced trials in Chapter 6.

The results from Chapter 7 identified five key themes. Collectively these themes indicate that it is likely a large percentage of the population do not accurately understand government guidelines for moderate intensity physical activity and are unaware of how moderate intensity should make them feel when being performed. Additionally, only three participants correctly identified the cardiovascular component of ‘150 minutes of moderate intensity or 75 minutes of vigorous physical activity a week’ described in UK NHS guidelines for physical activity (nhs.uk, 2022). These findings agree with existing physical activity awareness literature (Knox et al., 2015; Vaara et al., 2019) that in general peoples’ understanding of physical activity guidelines is poor.

Participants were asked to describe what types of exercise might allow them to reach moderate intensity. Exercise modalities and the descriptors used to define intensity by participants provided rich results. Common exercise modes that participants perceived to elicit moderate intensity were, walking, jogging, and cycling. While it is likely the physical laboratory trials may have created bias in participants’ responses and thus walking was the most common answer, the way in which participants described these exercise modes was nearly always ‘brisk, power, or fast walk,’ compared to a ‘gentle, light, or easy jog or cycle.’ These descriptors are not officially standardised, but previous literature has advocated for the standardisation of walking descriptors as very slow, slow, average, or brisk/fast’ (Syddall et al., 2015; Stamatakis et al., 2018). More interestingly is the high number of respondents suggesting jogging is a form of moderate intensity. Jogging is not described in the NHS guidelines, but running is a form of vigorous activity (NHSinform, 2022). This may have been intentional, as authors have reported jogging to elicit vigorous intensity (Kilpatrick et al., 2009; Schnohr Peter et al., 2015).

The subjective responses used to describe moderate intensity in UK NHS guidelines (nhs.uk, 2022) generated a number of subthemes in response to questions focussed on the subjective guidelines of ‘increased breathing, raised heart rate, and feeling warmer’ (nhs.uk, 2022). Breathing rate was associated with deeper breaths or an increased breathing rate, which may not be useful in specifically quantifying moderate intensity. One participant referred to the change from nasal breathing to oronasal breathing as an indicator of moderate intensity. There is a paucity of previous research highlighting the change from nasal to oronasal breathing as an indicator of physical activity intensity. However, previous findings indicated that the transition is associated with a mean (SD) RPE of 13 (2) (Niinimaa, Cole, Mintz, & Shephard.1980), which is associated with the descriptor of ‘moderate’. This transition from nasal to oronasal breathing as an indicator of moderate intensity is worthy of additional investigation.

Participants also referred to an increased body temperature with associated perspiration, or the need to remove a layer of clothing. These indicators as a measure of intensity are limited by several factors such as external temperature, number of layers worn, and the thickness of those layers. Perspiration is also impacted by these factors and as such may not be useful indicators of physical activity intensity, especially in the UK where seasons can substantially impact the external temperature and clothing worn. The final measure was an increased heart rate, which while easier to quantify objectively (through a wearable device), the use of heart rate as a subjective measure of exercise intensity was difficult to quantify for participants, which replicates previous findings (Yamaji, Yokota and Shephard, 1992).

Collectively these findings support the monitoring and prescription of relative measures of physical activity intensity through wearable devices as a more accurate method of monitoring physical activity at both individual and population levels. People's perceptions of wearable technology, specifically nudge theory and its use to promote physical activity, is worthy of investigation. Previous literature has indicated a spectrum of opinions on using nudge theory to promote physical activity. Peoples' concerns are that nudge theory corrupts personal autonomy (Schmidt and Engelen, 2020). However, there is also opportunity for nudge theory, especially in personal technologies, to improve physical activity (Schmidt and Engelen, 2020; Mamede et al., 2021). In light of this, Chapter 8 sought to obtain a better understanding of people's perceptions of nudge theory to guide walking cadence, with semi-structured interviews taking place after participants had completed laboratory trials described in Chapter 6.

The results from Chapter 8 indicated that participants in general would be open to the use of nudge theory to promote physical activity if it was of benefit to their cardiovascular health. The use of a metronome as a cadence cue was met with some conflicting opinions though. Participants perceived the metronome cue to be irritating when played throughout the 10-minute trial performed in Chapter 6. Additionally, participants highlighted that they were uncertain whether this method of cadence cueing would be applicable in a real world setting where navigating infrastructure and other pedestrians may inhibit one's ability to synchronise effectively with the cadence cue. Participants identified that it may be useful as a training tool, whereby the cadence cue could be turned on and off with ease by the person using it, to gauge the required walking cadence, and then be able to walk freely without the cadence cue playing continually. Additionally, several participants advocated the use of music as a more favourable method of cadence cueing, although this may not be plausible as several other contributing factors highlighted in Chapter 6 impact walking cadence when listening to music.

The haptic cue may have been participants' favoured method of cueing cadence as participants perceived this method to be less invasive than the metronome. However, the haptic cue strength was a limiting factor and participants reported not being able to feel the haptic during arm swing. Personal observation of the latest Apple Watch suggests that the haptic strength has been increased compared to the Series 5 Watches used in this thesis. Overall, there is scope for using cadence cues as a method of guiding people to walk at a cadence that elicits moderate intensity, and further investigation using different methods such as music, and stronger haptic cues are worthy of investigation.

As previously outlined in Chapter 3, the lead investigator's research paradigm and methodology used in the qualitative chapters (Chapters 7 and 8) were described. It is important to reflect on how this may have influenced the results of these chapters as the investigator is a critical component in data collection, analysis, and interpretation. A post positivist approach was used to analyse the data, as such positivism identifies a single reality, that is possible to understand and measure. This may have influenced how certain themes emerged, for example the quantification of participants' correctly identifying government guidelines for physical activity. This was done in a quantitative way with numerical values, yet in other philosophical paradigms it is unlikely quantification of ‘correct answers’ would have been reported. Additionally, the philosophical standpoint, specifically the epistemological stance whereby ‘a reality exists from human conjecture’ is likely to have influenced the analysis. It is possible this paradigm has influenced the results, for example, participants referred to their subjective feeling during moderate intensity which was analysed and contrasted with previous literature. In some cases, participant interpretations were questioned such as perspiring at moderate intensity, with evidence to suggest that moderate intensity is unlikely to cause perspiration. However, in an individual’s reality, perspiration during moderate intensity physical activity may be a reality. While the lead investigator’s axiological stance was to remove as much bias as possible by using scientific methodology, it is evident based on the lead investigator’s history of working and socialising in exercise and physical activity settings, that the lead investigator’s bias on the potential benefits of physical activity may have impacted data analysis and interpretation.

9.2 General conclusions

Implementing relative measures of physical activity such as %HRR when monitoring and prescribing physical activity should be considered essential for practitioners, governmental guidelines, and physical activity researchers alike. The significance of this, on a population basis, has the potential to increase physical activity intensity and thus may improve the associated health outcomes that are accompanied with moderate intensity physical activity. First, this thesis can conclude that there are large discrepancies between absolute and relative measures of physical activity intensity. Furthermore, it is evident that absolute measures of physical activity such as METS are incorrectly measuring physical activity for large portions of the population. An individualised approach to physical activity guidance is required and needs to be considered when implementing exercise guidance. Additionally, to approach this, and more accurately prescribe and monitor physical activity at a population level, wearable technology should be considered. Modern wearable devices like the Apple Watch can now reasonably accurately measure important variables such as resting heart rate from historical stored data (e.g., 7 – day mean resting heart rate). Wearable devices offer an opportunity to disseminate individualised physical activity guidance on a large-scale population basis. Ultimately this thesis advocates the use of wearable technology to promote relative physical activity with good accuracy. If applied correctly, the findings of this thesis have the potential to influence government guidelines, practitioners, and researchers in the implementation of relative measures of physical activity via wearable devices.

9.3 Limitations

The aims of this thesis were (1) examine the agreement and relationship between %HRR and METs, (2) examine how well %HRR as measured by the Apple Watch compares to criterion intensity (VO_2R) and the native Apple Watch Activity app for measuring moderate intensity while walking, (3) examine the plausibility of guiding walking cadence to meet relative moderate intensity via metronome and haptic feedback from the Apple Watch, (4) examine the perceptions of participants surrounding the use and knowledge of moderate intensity and physical activity guidelines, and (5) examine the perceptions of participants on wearable technology. This section aims to address some of the potential limitations associated within the experimental chapters.

Multiple studies have reported the need for individualised relative intensity physical activity monitoring (Serrano et al., 2017; O'Brien et al., 2018; Abt et al., 2019; Gil-Rey, Maldonado-

Martín and Gorostiaga, 2019). One of the limitations with this method is the lack of gold standard relative measure. This thesis predominantly focussed on %HRR as a relative measure of physical activity intensity. Although %HRR is individualised to a certain extent, the use of fixed percentages to define intensity categories (e.g., 40 – 59% HRR equates to moderate intensity) has some limitations, as it does not reflect a real physiological threshold, and as such is an arbitrary value. Physiological markers such as ventilatory or lactate thresholds reflect true individualised values of intensity and as such would be a better method of individualising physical activity intensity (Weatherwax et al., 2019; Lehtonen et al., 2022; Martini et al., 2022). However, at current this limitation exists in part due the capacity of wearable devices to measure such physiological mechanisms, and therefore, %HRR may currently offer the most accurate relative measure available at a population level. From a technological perspective the capacity to measure ventilatory thresholds will be a challenging development for wearable device manufacturers but would allow for a fully individualised measure of relative intensity, that would hypothetically, be available at a population level.

Another potential limitation in using relative moderate intensity, at a population level is the impact CRF has on fixed percentage boundary thresholds. As a person's CRF improves the heart rate response to a walking speed that previously would've induced moderate intensity is likely to stimulate a heart rate response below the threshold for moderate intensity. Therefore, to enable relative moderate intensity to be achieved with improving CRF, the 'goal posts,' in this case the walking speed is likely to increase. As the walking speed increases, the ability to achieve moderate intensity becomes more difficult, which could be demotivating, as the exercise being performed is deemed to be of higher intensity (Ekkekakis et al., 2023).

One of the potential limitations in Chapter 4 was the range of values used within the meta regression. As the focus of this thesis is moderate intensity, a large proportion of data points are categorised as moderate intensity and may impact the ability of the meta regression to capture the agreement between absolute and relative intensity across the spectrum of exercise intensities. In future studies, including activity that causes light and vigorous intensity such as running, would allow for a comparison of absolute and relative intensity over a wider range of exercise modes and intensities.

The MVPA app developments and potential limitations within its capabilities requires some consideration, while the app was specifically built to guide walking cadence, the Apple Watches capabilities meant several revisions were required. The haptic engine strength impacted the overground trials completed in Chapter 6. The haptic engine within the Apple Watch has been designed to notify the wearer for nudge notifications such as messages that are designed to 'nudge' the user once. As there is no specific haptic designed to continually nudge the user within the Watch's current capacity, as the MVPA's app was designed to do when cadence cueing, an amalgamation of haptic vibrations had to be used. This meant that the vibrations could not be administered with every foot strike but had to be administered for every other foot contact, as the haptic engine needed a recovery period after administering each haptic cue. This meant that if the cadence required to reach moderate intensity was 140 steps·min^{-1} the Watch would administer a haptic cue at a rate of 70 beats·min^{-1} i.e., every other foot strike. Additionally, several participants stated they struggled to feel the haptic cue as the vibration was not strong enough during arm swing (Chapter 8). This is likely to have impacted participants ability to synchronise with the haptic cue.

Additionally, the MVPA app had a design constraint that may have impacted participants ability to synchronise their walking cadence with the cadence cue. The Watch's capacity to modify cadence cue dependent on heart rate was designed to increase the cue tempo if heart rate was not above the 40% HRR threshold for moderate intensity. However, an oversite in its design meant that if a participants %HRR was within the 40 – 45% threshold, and for example, the cadence cue was administering a metronome or haptic cue at a rate of 150 beats·min^{-1}, but the participants walking cadence was below this tempo e.g., 120 beats·min^{-1}, the app did not recognise this and reduce the cadence cue tempo to match the participants walking cadence, it would continue to administer the cadence cue at the same rate. While this had no impact on guiding the participant to 40% HRR, it did impact participants ability to sycnhronise to the cadence cue.

Another limitation within the MVPA app design was that it was a beta version of the app. The lack of useability and basic interface meant that the app was not suitable for Appstore realease. This meant that the app had to be downloaded via TestFlight. TestFlight is an online service for mobile applications offered to developers within the IOS developer programme. All participants were required to download TestFlight and obtain the app in this manner, in order to take part in the study.

While self-paced trials were designed to reduce as much bias as possible, in that all participants were given the same instructions to walk at moderate intensity as desribed in the NHS guidelines (nhs.uk, 2022), it is possible the self-paced trials may have been impacted by the instructions given to participants prior to performing trials. This meant rather than walking at a cadence that adequately met moderate intensity, some participants may have walked as fast as they were able in order to ensure intensity was high enough. Previous findings suggest that people tend to exercise more vigorously when instructed to walk at a moderate intensity to ensure they are performing physical activity adequately, rather then being able to guage moderate intensity accurately (Braham, Rosenberg and Begley, 2012). In hindsight, initially performing an additional trial whereby participants are asked to walk at their normal walking speed, with no specific instruction, would have provided useful additional data.

Finally, the qualitative trials, while designed to reduce bias as much as possible with a semi-strcutured interview, were influenced by the laboratory trials performed prior to the interviews. Participants were aware that the study focussed on moderate intensity walking, which may have created bias in some of their responses to questions, epecially on modalities that may elicit moderate intensity. One of the most common answers given to this question was walking which is likely impacted by the physical laboratory trials. Additionally, when participanrts were asked how moderate intensity might make them feel, participants may have used the laboratory trials that they had just performed as a marker of intrinsic feeling to guide their responses in the interview.

Despite these limitations, the thesis has followed robust scientific protocols throughout. By following these processes, we believe we have provided data that is high in quality and scientific rigour.

9.4 Future recommendations

The review of the literature and the findings of this thesis suggest that research into relative measures of physical activity and the use of wearable technology is still a developing research area. While research into relative measures of physical activity intensity has been developed over many years, the implementation at a population level has never been feasible. Wearable technology now offers the opportunity to promote individualised relative measures of physical activity monitoring and prescription to the mass population. As a result of this thesis, it is clear that absolute measures of physical activity are likely inaccurately measuring physical activity for a large percentage of the population.

As highlighted in Chapters 4 and 5, there are large discrepancies between absolute and relative measures of physical activity, with results from this thesis and a growing bank of literature (Serrano et al., 2017; Abt et al., 2019; Gil-Rey, Maldonado-Martín and Gorostiaga, 2019) indicating relative individualised measures of physical activity are required to improve accuracy of physical activity monitoring and prescription. Therefore, the future recommendations based on the relative measures of physical activity data in this thesis, would be to consider using relative measures of physical activity monitoring and prescription at a population level, through wearable devices. Additionally, when recording moderate intensity via the Apple Watch when measured against the criterion measure of relative intensity, $\%VO_2R$, results indicated a low level of variance (Bayesian $R^2 = 0.66$). Based on these findings and previous literature (Khushhal et al., 2017; Abt, Bray and Benson, 2018) these devices have been shown to be capable of measuring moderate relative intensity with good accuracy, thus using relative measures within wearable devices to monitor physical activity continually is recommended. While %HRR may currently be the best option for monitoring physical activity at a population level, a challenging future recommendation, from a technological perspective, will be for manufacturers of wearable devices to incorporate sensors capable of measuring physiological markers such as ventilatory threshold. When this technological challenge has been met, it will allow a fully individualised measure of relative intensity available at a population level.

While wearable technology has the capacity to accurately monitor individualised relative physical activity, and the ever-growing wearables market suggests that these methods could be implemented at a population level, it is worth highlighting that not all people will have access to wearable technology. It is therefore important to also discuss future recommendations for government guidelines for physical activity. Currently, as highlighted in Chapter 7, people interpret the NHS guidelines to moderate physical activity in several ways. These interpretations may be useful in directing future recommendations for physical activity intensity. At current there is limited evidence on how government guidelines are interpreted, and therefore there are several opportunities that warrant further investigation. As indicated in previous literature (Braham, Rosenberg and Begley, 2012) and touched upon in Chapter 6, when instructed to exercise at moderate intensity people often tend to ignore guidelines and exercise at the highest intensity they are able to do so, to ensure they are performing exercise at, what they deem to be, a suitable intensity. Additionally, as highlighted in Chapter 7 and previous literature (Vaara et al., 2019; Piercy et al., 2020) people's awareness of government guidelines for physical activity are generally poor. With this in mind it is important that physical activity guidelines guide people to the appropriate physical activity intensity, duration, and dose for the associated cardiorespiratory benefits (Jensen et al., 2012; Kang, Ha and Ko, 2017; Al-Mallah, Sakr and Al-Qunaibet, 2018) but also to improve adherence (Ekkekakis et al., 2023). As such it would appear important to further investigate the usefulness of current physical activity guidelines, with the subjective descriptors for exercise intensities possibly requiring modification to improve the interpretation of such guidelines at a population level.

9.5 Practical applications

This thesis was conducted with a population ranging in age and fitness status allowing for several important practical findings to be made that are relevant to practitioners, and researchers, working to devise exercise guidance at a population level. As such this thesis has highlighted several practical applications.

1. There is a clear need to better quantify physical activity at a population level using relative physical activity intensity variables.
2. The use of METS and data derived from METS used as guidance for physical activity should be examined as it is likely misinterpreting physical activity intensity for a large percentage of the population.
3. At current, %HRR that takes into consideration a measure of cardiorespiratory fitness (resting heart rate) may offer the best option at a population level using wearable technology.
4. Other relative intensity variables that do not use fixed percentage boundaries to quantify intensity should be considered as the most individualised methods of quantifying physical activity intensity, and as such sensors within wearable devices should consider the ability to measure such variables as ventilatory thresholds for future wearable device development.

5. The Apple Watch overestimates moderate intensity physical activity, however if relative measures such as %HRR are used to monitor physical activity, wearable devices should be considered as an accurate method of disseminating physical activity intensity guidance and monitoring at a population level.
6. The use of metronome and haptic cadence cues requires additional investigation as methods of cadence cueing.
7. NHS guidelines for physical activity may require amending to ensure more accurate interpretation.

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11. Appendices

11.1 Appendix A

	Question	Operational definition	Scoring system
1	Is the hypothesis/ aim/ objective of the study clearly described?	Were all three provided, report accordingly in qualitative analysis. Point given if 1 of 3 are clearly described.	1 – Yes 0 – No
2	Are the main outcomes to be measured clearly described in the introduction or Methods section?	Do they clearly state the primary and secondary outcomes.	1 – Yes 0 – No
3	Are the characteristics of the participants included in the study clearly described?	Means and SD reported for participants characteristics.	1 – Yes 0 – No
4	Are the main findings of the study clearly described?	Are summary data clearly presented in table format? Is there a textual description of the main findings.	1 – Yes 0 – No
5	Does the study provide estimates of the random variability in the data for the main outcomes?		1 – Yes 0 – No
6	Have actual probability values been reported (e.g., 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?	0.035 rather than <0.05 for the main outcomes except where the probability value is less than 0.001? All P values must meet the criteria consistently.	1 – Yes 0 – No

7	Were the participants asked to participate in the study representative of the entire population from which they were recruited?	Relates to initial recruitment not participation. Have they accurately identified the population (title, intro, methods).	1 – Yes 0 – No
8	Were those participants who were prepared to participate representative of the entire population from which they were recruited?	Do the participants who participated closely correspond to the population identified (title, intro, methods).	1 – Yes 0 – No
9	Were the hypotheses of the study pre-registered? (And a link provided to the registration)	Should be reported if completed.	1 – Yes 0 – No
10	Were the statistical tests used to assess the main outcomes appropriate?	The statistical techniques used must be appropriate to the data. For example, nonparametric methods should be used for small sample sizes. Where little statistical analysis has been undertaken but where there is no evidence of bias, the question should be answered yes. If the distribution of the data (normal or not) is not described, it must be assumed that the estimates used were appropriate and the question should be answered yes.	1 – Yes 0 – No
11	Were the validity of the main outcome measures reported and/ or established?	Needs to be reported, referenced, with a valid and reliable method	1 – Authors have reported a valid accurate and reliable dependent variable, with verification of accuracy, reliability and validity. 0 - If they are reported but not accurate 0 - If they are not reported – unable to determine

12	Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?	1 – If adjustment wasn’t required 1 – if adjustment was required and completed 0 – if adjustment was required but was not completed
13	Did the study perform a power calculation, report associated inputs and recruit the required number of participants?	1 - Apriori power calculation was completed, no associated inputs recorded, did not recruit the required number of participants 2 - Apriori calculation has been completed, no inputs have been reported, successfully recruited the required participants 3 - Apriori calculation was completed with associated inputs reported, but didn’t recruit required participant numbers 4 - Apriori power calculation was completed with associated inputs reported, and recruited required participants

11.2 Appendix B

STROBE Statement—Checklist of items that should be included in reports of ***cross-sectional studies***

	Item No	Recommendation
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found
Introduction		
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported
Objectives	3	State specific objectives, including any prespecified hypotheses
Methods		
Study design	4	Present key elements of study design early in the paper
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection
Participants	6	(*a*) Give the eligibility criteria, and the sources and methods of selection of participants
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group
Bias	9	Describe any efforts to address potential sources of bias
Study size	10	Explain how the study size was arrived at
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why
Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding
		(*b*) Describe any methods used to examine subgroups and interactions
		(*c*) Explain how missing data were addressed
		(*d*) If applicable, describe analytical methods taking account of sampling strategy
		(*e*) Describe any sensitivity analyses
Results		
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed
		(b) Give reasons for non-participation at each stage
		(c) Consider use of a flow diagram
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders
		(b) Indicate number of participants with missing data for each variable of interest
Outcome data	15*	Report numbers of outcome events or summary measures
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included
		(*b*) Report category boundaries when continuous variables were categorized
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses

Discussion		
Key results	18	Summarise key results with reference to study objectives
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence
Generalisability	21	Discuss the generalisability (external validity) of the study results
Other information		
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based

*Give information separately for exposed and unexposed groups.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.

11.3 Appendix C

BREATHLESSNESS

0	No Breathlessness, Nothing at all
0.5	Very, very slight (just noticeable)
1	Very Slight
2	Slight Breathlessness
3	Moderate
4	Somewhat severe
5	Severe Breathlessness
6	
7	Very Severe Breathlessness
8	
9	Very, very severe Breathlessness
10	Maximum Breathlessness

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

THERMAL SENSATION

"How does the temperature of your body feel?"

1	**Unbearably cold**
2	**Extremely cold**
3	**Very cold**
4	**Cold**
5	**Cool**
6	**Slightly cool**
7	**Neutral**
8	**Slightly warm**
9	**Warm**
10	**Hot**
11	**Very hot**
12	**Extremely Hot**
13	**Unbearably hot**

11.4 Appendix D

COREQ (COnsolidated criteria for REporting Qualitative research) Checklist

A checklist of items that should be included in reports of qualitative research. You must report the page number in your manuscript where you consider each of the items listed in this checklist. If you have not included this information, either revise your manuscript accordingly before submitting or note N/A.

Topic	Item No.	Guide Questions/Description	Reported on Page No.
Domain 1: Research team and reflexivity			
Personal characteristics			
Interviewer/facilitator	1	Which author/s conducted the interview or focus group?	
Credentials	2	What were the researcher's credentials? E.g. PhD, MD	
Occupation	3	What was their occupation at the time of the study?	
Gender	4	Was the researcher male or female?	
Experience and training	5	What experience or training did the researcher have?	
Relationship with participants			
Relationship established	6	Was a relationship established prior to study commencement?	
Participant knowledge of the interviewer	7	What did the participants know about the researcher? e.g. personal goals, reasons for doing the research	
Interviewer characteristics	8	What characteristics were reported about the inter viewer/facilitator? e.g. Bias, assumptions, reasons and interests in the research topic	
Domain 2: Study design			
Theoretical framework			
Methodological orientation and Theory	9	What methodological orientation was stated to underpin the study? e.g. grounded theory, discourse analysis, ethnography, phenomenology, content analysis	
Participant selection			
Sampling	10	How were participants selected? e.g. purposive, convenience, consecutive, snowball	
Method of approach	11	How were participants approached? e.g. face-to-face, telephone, mail, email	
Sample size	12	How many participants were in the study?	
Non-participation	13	How many people refused to participate or dropped out? Reasons?	
Setting			
Setting of data collection	14	Where was the data collected? e.g. home, clinic, workplace	
Presence of non-participants	15	Was anyone else present besides the participants and researchers?	
Description of sample	16	What are the important characteristics of the sample? e.g. demographic data, date	
Data collection			
Interview guide	17	Were questions, prompts, guides provided by the authors? Was it pilot tested?	
Repeat interviews	18	Were repeat inter views carried out? If yes, how many?	
Audio/visual recording	19	Did the research use audio or visual recording to collect the data?	
Field notes	20	Were field notes made during and/or after the inter view or focus group?	
Duration	21	What was the duration of the inter views or focus group?	
Data saturation	22	Was data saturation discussed?	
Transcripts returned	23	Were transcripts returned to participants for comment and/or	

Topic	Item No.	Guide Questions/Description	Reported on Page No.
		correction?	
Domain 3: analysis and findings			
Data analysis			
Number of data coders	24	How many data coders coded the data?	
Description of the coding tree	25	Did authors provide a description of the coding tree?	
Derivation of themes	26	Were themes identified in advance or derived from the data?	
Software	27	What software, if applicable, was used to manage the data?	
Participant checking	28	Did participants provide feedback on the findings?	
Reporting			
Quotations presented	29	Were participant quotations presented to illustrate the themes/findings? Was each quotation identified? e.g. participant number	
Data and findings consistent	30	Was there consistency between the data presented and the findings?	
Clarity of major themes	31	Were major themes clearly presented in the findings?	
Clarity of minor themes	32	Is there a description of diverse cases or discussion of minor themes?	

Developed from: Tong A, Sainsbury P, Craig J. Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care*. 2007. Volume 19, Number 6: pp. 349 – 357

Once you have completed this checklist, please save a copy and upload it as part of your submission. DO NOT include this checklist as part of the main manuscript document. It must be uploaded as a separate file.

11.5 Appendix E

Topic guide

At the beginning of all interviews

- The researcher will introduce themselves to the participant.
- The researcher will explain the study and the purposes of the interview.
- The researcher will explain that they would like to audio-record the interview and processes for ensuring anonymity and confidentiality of interview data.
- The researcher will explain how interview data will be used.
- The researcher will determine if the participant would like to take part in the study and if so, will obtain written informed consent.
- Participants will be provided with the opportunity to ask any questions.
- Participants will be told they can stop the interview at any point without having to give reason.

This topic guide summarises the main areas to be explored for each interview. As with any qualitative interview, these headings are intended as a starting point to ensure the primary issues are covered, whilst allowing flexibility for new issues to emerge.

- Researcher to ask brief details about age, occupation, to frame and contextualise the interview.
- What do you think the current government guidelines for physical activity are?
- What sort of physical activity might be classed as moderate intensity?
- How do you think moderate intensity might feel like when being performed?
- When you walk what do you think about?
- When walking does you think about your heart rate, ability to talk or whether you are getting warmer?
- NHS guidelines suggest moderate intensity activity should feel like you are getting warmer, your heart rate increases, but you should still be able to hold a conversation. Based on this information would you know how fast you might need to walk to achieve moderate intensity? How fast do you think that speed is? Could you demonstrate this on a treadmill?
- How important to you is meeting the current physical activity guidelines?
- Are you aware of any mass media campaigns related to physical activity?

At the end of the interview

- Thank participant and ask if they have any comments.
- Explain again about how data will be used and reiterate about anonymity and confidentiality.
- Provide opportunity for questions and state that the lead researcher is contactable after the interview, should questions arise.

11.6 Appendix F

Topic guide

At the beginning of all interviews

- The researcher will introduce themselves to the participant.
- The researcher will explain the study and the purpose of the interview.
- The researcher will explain that they would like to audio-record the interview and that appropriate processes for ensuring anonymity and confidentiality of interview data will be used.
- The researcher will explain how interview data will be used.
- Participants will be provided with the opportunity to ask any questions.
- Participants will be told they can stop the interview at any point without having to give reason.

This topic guide summarises the main areas to be explored for each interview. As with any qualitative interview, these headings are intended as a starting point to ensure the primary issues are covered, whilst allowing flexibility for new issues to emerge.

- Were any of the trials performed in the laboratory today, close to your normal walking speed, if so which trial?
- Did you walk slower/the same/ or faster with the metronome cue, compared to your normal walking speed?
- Did you walk slower/the same/ or faster with the haptic cue, compared to your normal walking speed?
- Did you walk slower/ the same/ or faster during your-self paced walking trial or when guided by cues?
- Would you use the metronome cue when walking outside?
- Would you use the haptic cue when walking outside?
- If the cadence cue had the ability to improve your cardiovascular health, by guiding you to the correct exercise intensity, would you be more inclined to use it?

At the end of the interview

- Thank participant and ask if they have any comments.
- Explain again about how data will be used and reiterate about anonymity and confidentiality
- Provide opportunity for questions and state that the lead researcher is contactable after the interview, should questions arise.