DOCTOR OF PHILOSOPHY (2023)
(Kinesiology)

McMaster University
Hamilton, Ontario

FACTORS AFFECTING PERCEIVED EXERTION

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FACTORS AFFECTING RATINGS OF PERCEIVED EXERTION ACROSS A SPECTRUM OF HEALTH AND DISEASE

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TITLE: Factors affecting ratings of perceived exertion across a spectrum of health and disease

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LAY ABSTRACT

It has been well established that heart rate and ratings of perceived exertion are related in young, healthy individuals, however the nuances of the relationships between other contributors and how clinical populations feel during exercise remain unclear. Using mixed methods, this research sought to determine what sensations help people determine how they feel during exercise, with a focus on high intensity interval training exercise. Our results show that muscle strength may be a key determinant in the perception of effort in individuals with a spinal cord injury and in clinical populations during arm and leg maximal graded exercise tests, but the relationships between physiological variables and perceptions of arm effort in non-impaired individuals remains to be determined. Sensations of effort are regulated through a variety of different mechanisms that vary with population, and the relationships depend on the parameters (e.g., exercise modality and intensity) of the exercise. Future studies should be conducted to determine the individual contributions of different body systems to perceived exertion during exercise in a wide range of populations.

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ABSTRACT

Perceived exertion is how hard or heavy an individual feels they are working. Perceived exertion is often quantified using the ratings of perceived exertion (RPE) scale and can be used to measure exercise intensity based on the experience of an individual. While objective methods of assessing exercise intensity, such as measurement of heart rate and percent of peak oxygen uptake, are useful, RPE is commonly implemented for the ease of use and feasibility. For example, RPE is commonly implemented in rehabilitation settings for people with a spinal cord injury and individuals with coronary artery disease because of their non-linear heart rate response to increases in exercise workload. The overarching purpose of this dissertation was to investigate a range of research questions designed to advance the knowledge and use of RPE guided exercise. Through a systematic review and meta-analysis, we examined evidence for the impact on cardiorespiratory fitness and peak power output using RPE-guided interventions in individuals with a spinal cord injury (SCI) and found that RPE-guided interventions improved both after a variety of exercise intervention types and lengths. In a separate retrospective cross-sectional analysis, we then demonstrated that perceived exertion, measured by leg cycling effort during a cardiopulmonary exercise test on a leg cycle ergometer in non-disabled individuals, was predicted by power and maximum power output. After further investigation we found that quadriceps strength predicted maximum power output and therefore is related to leg cycling effort. In the third study of the thesis, we conducted semi-structured interviews in individuals with an SCI and their healthcare practitioners and found that individuals commonly described their sensations associated with the 0-10 RPE scale using muscle sensations when both recalling exercise and after the completion of an acute exercise trial on an arm cycle ergometer. Lastly, we investigated the relationship between psychological and physiological measures and RPE during an arm cycling exercise during a maximal graded exercise test, high intensity interval training, and moderate intensity continuous training using a crossover experimental design in both non-disabled individuals and individuals who were mobility impaired due to SCI. While there were no relationships between any variable and RPE in non-disabled individuals, age and triceps strength predicted central RPE and peak feeling scale predicted peripheral RPE in individuals with an SCI. These mixed methods results collectively suggest that muscle strength, not heart rate, is the strongest predictor of perceived exertion especially in clinical populations completing high intensity exercise. Our novel findings suggest that RPE is regulated through a system of psychological and physiological phenomena, strongly related to muscle sensations arising from the working muscle groups and may have utility and relevance in complementing measures of exercise intensity for a broad range of individuals across the spectrum of health and disease. Future studies should examine the use of muscle sensation descriptions as descriptors of exercise intensity prior to the development of high intensity exercise guidelines in clinical populations, such as individuals with SCI.

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“Certainty is the enemy of change.” – Esther Perel

DEDICATIONS

To my participants, you taught me so much more than I ever can express through this thesis. The stories you have shared are lessons that will last my lifetime. You make the science make sense. Moving our bodies is so much more than just exercise, it's how we live.

“My driving force for me was that I want to live.”

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LIST OF ABBREVIATIONS AND SYMBOLS

AD	Autonomic dysreflexia
$a\text{-}vO_2$	Arterial venous oxygen
[BLa]	Blood lactate concentration
[BLa]peak	Peak blood lactate concentration
BMI	Body mass index
BP	Blood pressure
B	Beta-coefficient
CO	Cardiac output
CPET	Cardiopulmonary exercise testing
CR10	Category Ratio 10
CRF	Cardiorespiratory fitness
DBP	Diastolic blood pressure
DLCO	Diffusing capacity for carbon monoxide
ECG	Electrocardiography
F	Female
FEV_1	Forced expired volume over 1 second
FS	Feeling scale
Hb	Hemoglobin
HIIT	High intensity interval training
HR	Heart rate
HRpeak	Peak heart rate
KCO	Carbon monoxide transfer coefficient

LTPA	Leisure time physical activity
M	Male
MANOVA	Multivariate analysis of variance
MAP	Mean arterial pressure
MEP	Maximum expiratory pressure
MIP	Maximum inspiratory pressure
MICT	Moderate intensity continuous training
O_2	Oxygen
$PECO_2$	Partial pressure of expired carbon dioxide
PEFR	Peak expiratory flow rate
$PETCO_2$	End-tidal carbon dioxide
PIFR	Peak inspiratory flow rate
P_{MAX}	Maximum power output
PO_{peak}	Peak power output
PP	Paraplegia
RER	Respiratory Exchange Ratio
RPE	Ratings of perceived exertion
RPE_P	Peripheral ratings of perceived exertion
RPE_C	Central ratings of perceived exertion
RQ	Respiratory quotient
1-RM	One repetition maximum
SBP	Systolic blood pressure
SCI	Spinal cord injury

SEE	Standard error of estimate
TEA	Task, effort, and awareness
TMD	Total mood disturbance
TP	Tetraplegia
$\dot{V}A$	Alveolar volume
VC	Vital capacity
V_E	Minute ventilation
$\dot{V}O_2$	Oxygen uptake
$\dot{V}CO_2peak$	Peak expired carbon dioxide
$\dot{V}O_2peak$	Peak oxygen uptake

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1 Introduction

1.1 Cardiorespiratory fitness

Cardiorespiratory fitness (CRF), quantified by peak oxygen uptake ($\dot{V}O_2$peak), was first described in 1923, by Hill and Lupton (Hill & Lupton, 1923). Higher levels of CRF are associated with lower risk of all-cause, and disease-specific mortality (Blair et al., 1989; Harber et al., 2017). CRF is recognized as providing important health information that can aid in the diagnosis and the prediction of future disease (Kodama et al., 2009; Ross et al., 2016). Traditional cardiovascular disease risk factors include age, total cholesterol, high-density lipoprotein cholesterol, systolic blood pressure, diabetes, and current smoking status, however in asymptomatic adults, CRF assessment provides additional predictive accuracy of future atherosclerotic cardiovascular disease risk (Fardman et al., 2020). CRF also plays a role in both primary and secondary disease prevention such that individuals with higher levels of CRF are at lower risk for cardiovascular disease and have a greater chance of survival after being diagnosed with cardiovascular disease (Safdar & Mangi, 2020). Research focused on “Physical activity as a vital sign” is an example of how CRF has recently been recognized to provide valuable health information and continues to play a transformative role in medical practice (Golightly et al., 2017).

People that participate in regular physical activity have an improved ability to complete activities of daily living (Roberts et al., 2017). Increased $\dot{V}O_2$peak translates to a lower percentage of cardiorespiratory demand during submaximal activity. Through structured exercise training and increasing activity levels, CRF can be improved, regardless of age, gender, race, and baseline level of CRF (Skinner et al., 2001). In a dose–response analysis, a one unit increment of metabolic equivalents (METs) in CRF was associated with a 13% and 15% risk reduction from all-cause mortality and cardiovascular disease events, respectively (Kodama et al., 2009). In addition to better survival, exercise training in the form of scheduled and planned sessions is commonly used to treat psychiatric, neurological, cardiovascular, pulmonary, metabolic and musculoskeletal diseases, and cancer, ultimately increasing the number of disease free years (Li et al., 2020; Pedersen & Saltin, 2015).

1.1.2 Exercise prescription for non-disabled individuals

The Canadian 24-hour movement guidelines suggest that physical activity plays an important role in the maintenance of CRF (Ross et al., 2020). Given the increasing amount of sedentary time in the modernized world, it is important to provide guidelines for movement to maintain physical health. Evidence-based guidelines define the minimum amount of activity required to attain the activity-induced benefits for protection against various mental and physical health conditions. Ideally, exercise prescription is tailored to meet the needs of the individual. Currently, we are unable to create wide-scale, individualized recommendations, however age- and ability-specific physical activity guidelines have also been developed through the conduct of systematic reviews and the examination of dose-response relationships between cardiometabolic health outcomes (Chaput et al., 2020; Martin Ginis et al., 2018; Mottola et al., 2018; Ross et al., 2020).

The Canadian Society for Exercise Physiology advises non-disabled adults aged 18-64 years to accumulate at least 150 minute of moderate- to vigorous-intensity aerobic physical activity per week, in bouts of 10 minutes or more, and muscle and bone strengthening activities using major muscle groups at least 2 days per week (Ross et al., 2020). These guidelines also state that more physical activity provides greater health benefits. The World Health Organization (WHO) suggests 300 minutes of exercise for additional health benefits, and all other recommendations are similar (Bull et al., 2020). A recent update to the physical activity guidelines for Americans (2018) suggests "moving more and sitting less" and the 24-hour movement guideline for children and youth, include maximum daily sedentary screen time of 2 hours (Piercy et al., 2018; Poitras et al., 2016). Sedentary time is described as any time spent in a seated, reclined, or lying posture, expending low levels of energy under 1.5 METs, however some activities that may be less than 1.5 METs for a non-disabled person likely requires higher metabolic demand for a person with spinal cord injury (SCI) (Todd & Martin Ginis, 2019). There is some evidence to suggest moderate physical activity can offset some of the risk associated with highly sedentary behaviour in non-disabled individuals (Ekelund et al., 2019). More research needs to be done to understand these relationships for individuals with SCI many of whom require a seated position in their wheelchair, necessary for mobility.

1.1.3 Spinal cord injury specific exercise prescription in Canada

In Canada, it is estimated that there are estimated to be over 30,000 people living with traumatic spinal cord injury, where 52% have paraplegia (PP) and 48% have tetraplegia (TP) (Thorogood et al., 2023). Between 768,473 people per year incur a traumatic spinal injury, worldwide (Kumar et al., 2018). Given a multitude of barriers, it is no surprise that individuals with SCI are amongst the lowest on the physical-activity-participation spectrum (Todd & Ginis, 2019). Of people with an SCI, 50% do not engage in any leisure-time physical activity (LTPA), which is a remarkable statistic, considering only exercise and sports have been shown to improve health and well-being for these individuals (Martin Ginis et al., 2010; van der Scheer et al., 2018). Exercise is a potent stimulus to maintain health after SCI and traditionally recommendations include moderate intensity continuous training according to the SCI-specific Canadian physical activity guidelines to improve physical fitness (Pelletier et al., 2015). Sixteen weeks of exercise training using the recommendations of the Canadian physical activity guidelines for individuals with an SCI (at least 20 minutes of moderate to vigorous intensity aerobic exercise 2 times per week and 3 sets of strength training exercise of major muscle groups 2 times per week) has been shown to improve cardiorespiratory fitness (Pelletier et al., 2015). The guidelines have since been updated to specify that the original guidelines are strongly recommended to provide CRF and muscle strength benefits (Martin Ginis et al., 2018). A conditional recommendation for 30 minutes of moderate to vigorous intensity aerobic exercise per week for cardiometabolic benefits was also added. Despite progress in developing SCI-specific guidelines, evidence-based recommendations on high intensity interval training (HIIT) and home-based exercise monitoring have not been addressed.

1.1.4 The role of exercise intensity

Physiological adaptations to exercise are mediated by the training volume that is completed (MacInnis & Gibala, 2017). Training volume is the product of the frequency, intensity, and duration of exercise, which each can influence the magnitude of improvement in $\dot{V}O_2$peak. Intensity is a strong mediating factor to adaptations that lead to improvements in CRF at a whole-body level (MacInnis & Gibala, 2017). In comparison to moderate intensity exercise, HIIT has been shown to lead to superior physiological adaptations in non-disabled populations (Gillen et al., 2016; MacInnis & Gibala, 2017). High intensity exercise can be more time-efficient which could address “lack of time”, a commonly cited barrier for adherence to exercise training programs (Kimm et al., 2006; Stutts, 2002; Trost et al., 2002). Despite these benefits, research on HIIT has been criticized for lack of population-level applications (Biddle & Batterham, 2015). In particular, it has been highlighted that the psychological challenges presented by HIIT may be more of a barrier to participation and adherence in some populations (Biddle & Batterham, 2015). Interestingly, a recent meta-analysis on affective responses found that participants experience lower affect during HIIT and more positive overall enjoyment after HIIT in comparison to moderate intensity exercise (Niven et al., 2020). The long-term adherence to HIIT has not been studied at population level, yet HIIT remains a valuable tool for specific populations interested in rapid physiological adaptations, independent of overall physical activity engagement.

Given the importance of exercise intensity for exercise prescription, valid and reliable measurement of intensity is essential. Unlike the other principles of exercise training such as frequency, time, and type of exercise; intensity can be expressed in both an absolute and relative scale, is dependent on the individual’s exercise capacity and can be calibrated to the maximal intensity of an individual. Consequently, exercise intensity is often expressed as a percentage of maximal capacity, for example, percentage of maximal heart rate (HR). Currently for aerobic exercise, the recommendation is to use direct measurements of $\dot{V}O_2$ and HR during exercise to provide accurate, individualised exercise prescription based on the physiological responses to exercise (Garber et al., 2011). Although these physiological methods of intensity prescription and monitoring are reliable, they are not feasible for population-wide uptake, especially for individuals with SCI in whom there are barriers to the determination of maximal capacity and monitoring of $\dot{V}O_2$ and HR.

Table 1. Classification of exercise intensity according to the American College of Sports Medicine. Adapted from Garber et al., 2011.

Intensity	**%$\dot{V}O_{2max}$**	**%HR_{max}**	**%HR reserve**	**RPE (6-20)**
Very light	< 37	< 57	< 30	< 9
Light	37-45	57-63	30-39	9-11
Moderate	46-63	64-76	40-59	12-13
Vigorous	64-90	77-95	60-89	14-17
Near maximal to maximal	≥ 91	≥ 96	≥ 90	≥ 18

$\dot{V}O_2$max = maximal oxygen uptake; HRmax = maximum heart rate; HR = heart rate; RPE = rate of perceived exertion

In addition, objective measures of intensity require equipment and techniques that must be applied with a high level of control with technical expertise in laboratory settings. Although some portable methods for $\dot{V}O_2$ and HR measurement are available, the cost associated may only be reasonable for individuals that are highly invested in exercise performance, such as high-level athletes. Individuals with a high neurological level of SCI have impaired sympathetic innervation of the heart (Krassioukov, 2009) which diminishes the validity of HR as an exercise monitoring tool for this population (van der Scheer et al., 2018). For these reasons, the use of HR and $\dot{V}O_2$ for intensity monitoring and prescription in community-dwelling individuals with SCI is not feasible and alternative methods should be explored. Subjective measures of intensity could be used to prescribe exercise intensity, though currently there is insufficient evidence to support this practice (Garber et al., 2011).

1.1.5 Altered acute HR responses to exercise

Compared to the non-disabled population, individuals with SCI experience reduced absolute physiological responses to both submaximal exercise and exercise training (Hjeltnes et al., 1998; Schmid et al., 1998; Van Loan et al., 1987). Despite altered absolute responses compared to non-disabled individuals, increased habitual physical activity increases CRF in individuals with SCI (Hicks et al., 2003). In both active and inactive men with paraplegia, there is a minimal increase in stroke volume (SV) and cardiac output (CO) acutely during arm ergometry (Davis & Shephard, 1988). During exercise the hemodynamic responses are blunted, which not only increases the risk of atherosclerosis and associated co-morbidities, but also impairs the individual's ability to improve cardiovascular function via exercise training (Astorino, 2019).

Individuals with coronary artery disease have been commonly prescribed beta-adrenergic blocking medications as an anti-hypertensive therapy for more than 50 years (Lund-Johansen, 1967; Steg et al., 2012). In stable coronary artery disease patients, a resting heart rate of >70bpm has been associated with an overall worse health status, and more frequent angina, and ischemia (Steg et al., 2012). Beta-adrenergic blocking medication inhibits beta-adrenergic signalling at the level of the heart, decreasing left ventricular contractility (Eston, 1997; Lund-Johansen, 1983). The use of beta-blockers results in a lower HR, [Bla], SV, CO, and systolic blood pressure (BP) at peak exercise

(Eynon et al., 2008). These hemodynamic changes are accompanied by higher arteriovenous oxygen difference (a-vO_2), an important protective factor for improved oxygen delivery and extraction at the level of the skeletal and heart muscle in individuals with coronary artery disease (Eynon et al., 2008). Alternative exercise intensity prescription modalities must be considered for individuals that have altered HR responses to exercise due to the prescribed use of beta-blockers,

Individuals with SCI above the level of T6 also have altered heart rate responses to exercise. Heart rate is decreased with increasing parasympathetic nervous system activation through the vagal nerve which is a cranial nerve. In contrast, exiting the spinal column at the vertebral level of C2 and C3, sympathetic innervation of the heart exits the spinal column at the vertebral levels from T6 to T9 and therefore the level of injury can influence the regulation of heart rate. Individuals with incomplete injuries above T6 may have partial cardiac innervation and the resulting level of sympathetic activation is dependent on the severity and type of injury.

Individuals with spinal injuries at the level of T6 and higher may have an increase in heart rate from a bottom-up phenomena (Krassioukov et al., 2014). This increase in heart rate is often caused by activation of nociceptors typically through bowel and bladder distention, pressure or other discomfort below the level of injury (Krassioukov et al., 2014). These mechanisms lead to an unchecked feedback loop, called autonomic dysreflexia, and can cause severe health problems if the cause of the rise in sympathetic activation goes unmanaged (Krassioukov et al., 2014). The amount of disruption on the autonomic nervous system can be assessed using the sit-up test (Tang et al., 2012). The sit-up test is a 10-minute test that entails monitoring blood pressure in response to a passive change in posture, from supine to seated. The distinct differences in upper and lower SCI justify reporting for research studies in this population to be disaggregated whenever possible. The typical classification is TP (above the level of T2) and individuals with PP (at the level of T2 or lower) (Herrmann et al., 2011). Individuals with TP and PP also experience different levels of thermoregulation, motor and sensory function, and altered organ function (e.g., respiratory function), that each contribute to the response to exercise (West et al., 2015). Given the complex nature of the spinal column, each injury is unique, and this lends itself to a heterogeneity of SCI population. Future work should aim to characterize all the levels of injury and the range of symptoms individuals may experience at each level of injury.

1.1.6 High intensity interval training for SCI

In non-disabled individuals, HIIT has been identified as an effective alternative to moderate intensity continuous training (MICT) (Gillen et al., 2016; MacInnis & Gibala, 2017), yet there has been limited research on the effects of varying exercise intensity in populations living with SCI. One previous study observed that when one bout of exercise was completed, there was a higher peak cardiorespiratory, metabolic and perceptual strain in the high intensity and sprint intensity protocols and both high and sprint intensity were preferred in comparison to MICT protocols by all participants (Astorino & Thum, 2018b). Within-session responses to high and sprint intensity exercise generated blood lactate concentration ([BLa]) that were comparable to the values at end of the maximal exercise test using the ramp protocol, which were significantly higher than [BLa] after MICT exercise in individuals with SCI (Astorino &

Thum, 2018a). These acute responses to exercise in individuals with SCI suggest that when compared to moderate intensity, high intensity exercise may lead to greater motor unit recruitment and metabolic processes that precede improvements in CRF. In a 6 week intervention, individuals with chronic SCI engaging in HIIT and MICT were found to improve their insulin sensitivity, peak aerobic capacity, muscle strength, and blood lipids (Graham et al., 2019). After 5 weeks of sprint interval training (SIT), participants with sub-acute SCI (<1 year time since injury) improved their peak power output to the same extent as those who trained using a MICT protocol for the same duration (McLeod et al., 2020). Two other studies examined the impacts of HIIT arm ergometry in combination with electrical stimulation of the lower extremity, which led to significant increases in $\dot{V}O_2$peak (Brurok et al., 2011; Hasnan et al., 2013). Two studies examined HIIT interventions using transferrable exercise modalities; 5-minute bouts of wheelchair ergometry (Tordi et al., 2001) and 2 rounds of 30s intervals of home-based wheelchair training (Gauthier et al., 2018). The studies had opposing results, whereby Tordi and colleagues found an increase in fitness determined by peak power output and $\dot{V}O_2$peak, while Gauthier and colleagues found no change in CRF or upper limb strength. Unfortunately, shoulder pain remained a concern for participants completing HIIT. Lastly, two studies employed 2 or 3 minutes of high intensity arm cycle ergometry (De Groot et al., 2003; Harnish et al., 2017), and found improvements in physical capacity from HIIT measured by $\dot{V}O_2$peak and peak aerobic power, respectively. Amongst the 8 studies completed to date, a total of 48 individuals with SCI have been involved in HIIT interventions, as revealed in recent perspective review (Astorino et al., 2020). Despite the lack of guidelines on high intensity exercise for individuals with SCI, people will continue to seek alternate forms of time-efficient exercise that suits their daily routine. More work needs to be done to understand the physiological underpinnings of HIIT. Individuals with SCI continue to engage in various exercises yet the physical activity guidelines does not share recommendations individuals on how to engage in HIIT in a safe and effective manner.

1.2 Ratings of Perceived Exertion

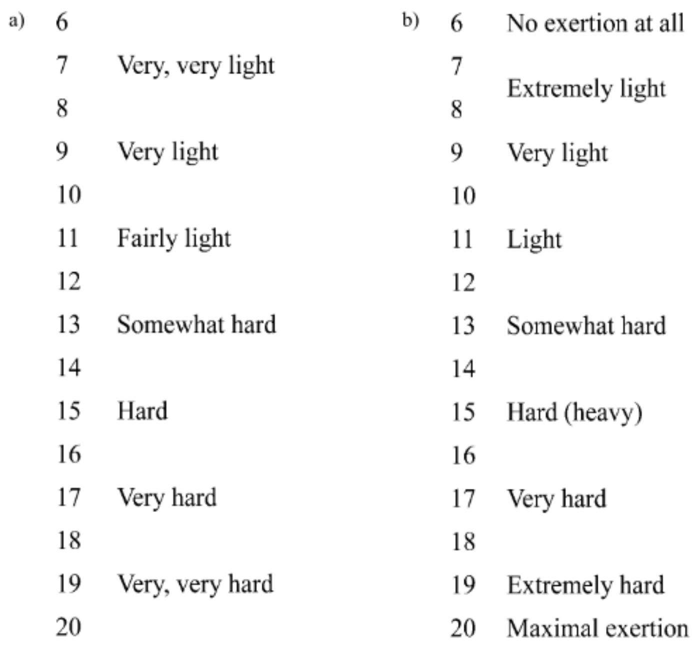
1.2.1 Origin of ratings of perceived exertion

The concept of ratings of perceived exertion (RPE) quantifies exertion during exercise (Borg, 1962; Borg & Dahlstrom, 1959), which led Dr. Gunnar Borg to construct the RPE scale that is the foundation of research in perception of exercise (Borg, 1970). This scale was originally developed in non-disabled men exercising on a leg cycle ergometer (Borg, 1962) and there is acceptable validity of the RPE scale for individuals with SCI based on a systematic review of applicable studies (van der Scheer et al., 2018). There have been multiple iterations of this scale, including the addition of verbal and visual aids (OMNI scale of perceived exertion) (Crytzer et al., 2015; Robertson et al., 2000, 2003, 2004), and abbreviated versions of the scale from the original 15-point (6-20 RPE scale) to the Category Ratio 1-10 (CR10) scale (Figure 2) (Borg & Ottoson, 1986). More recently research using artificial intelligence showed the capacity of an algorithm to detect exertion based on participant facial expressions, including the nose wrinkling and mouth openness, during exercise that was comparable to participant ratings (Timme & Brand, 2020). It has been suggested that future iterations of the RPE scale may wish to draw inspiration from the Fatigue scale that uses stick figure icons to define each level of fatigue and has been validated for use without instructions (Micklewright et al., 2017), reducing another barrier associated with prescribing exercise intensity.

Borg defined perceived exertion as the degree of heaviness and strain experienced during physical work (Borg, 1962). Importantly, Borg's definition of perceived exertion states that feedback from physiological systems impacts RPE, but that motivational factors can also exert an influence (Borg, 1998). Definitions of RPE include perception of "aches" (Borg, 1998) and discomfort (Noble & Robertson, 1996), although participants have subsequently been shown to differentiate both perceptions from the perception of exertion (Astokorki & Mauger, 2017; Christian et al., 2014; Groslambert et al., 2006). Perceptions of exertion can also be split into differentiated ratings of peripheral (RPE_P), central (RPE_C), and overall (RPE_O) exertion (Hutchinson, 2019), however it has been suggested that parsing out different regional sensations may detract from the overall definition and complicate the participant's understanding of RPE (Halperin & Emanuel, 2019).

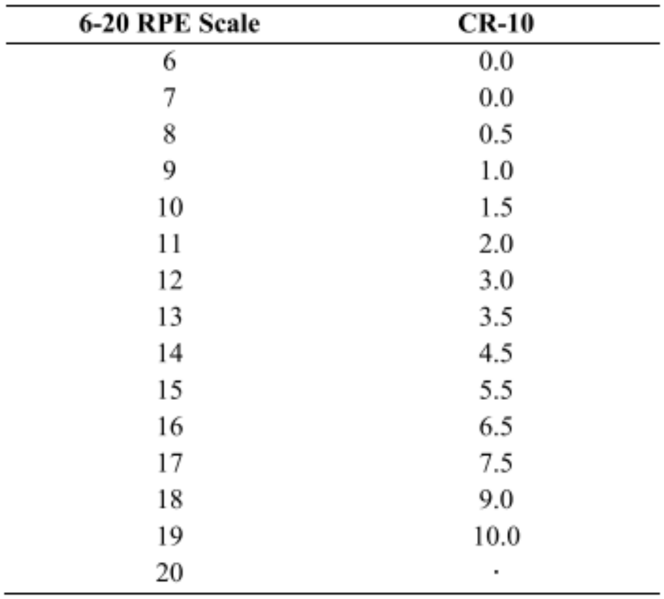
It has been demonstrated that how RPE is explained and instructed can impact the accuracy of the RPE scale in capturing exertion, and it is generally accepted that exertion can be distinguished from fatigue, discomfort, or pain (Halperin & Emanuel, 2020). There have been calls to separate the use of effort and exertion that seem to be driven by experts in the field of exercise psychology (Abbiss et al., 2015), in contrast to others that continue to use the terms effort and exertion interchangeably (Pageaux, 2016; Venhorst et al., 2018). Based on the field of neurophysiology, the brain areas associated with sensing a change in effort may be the insula and are closely related to fatigue studied in individuals with mild traumatic brain injury (Ramage et al., 2019). During imagined exercise, the insula and anterior cingulate cortexes may play a role in the cardiovascular responses, independent of muscle afferent feedback (Williamson et al., 2002). Alternatively, the brain areas associated with sustained effort might be the medial pre-frontal cortex and medial parietal cortex (Radel et al., 2017; Ramage et al., 2019). Studies examining the brain areas associated with volitional exercise do not differentiate between effort and exertion and instead focus on the integration of the signals in the cortical autonomic network to relay cardiovascular control signals to meet the demands of exercise (Al-Khazraji & Shoemaker, 2018). The state of the literature on effort and exercise is vast and there are a broad range of experimental trials that support different hypotheses and theories. For the purpose of this thesis, we will view effort and exertion as interchangeable, however we assert that pain, discomfort, and fatigue are sensations that can be differentiated. Future research should aim to examine the brain areas associated with effort and exertion during the time course of both steady state and interval style exercise to integrate and reconcile knowledge across each discipline.

Borg's RPE scale is highly useful to gauge exercise intensity for many practical settings. RPE is more practical than objective measures of exercise intensity (i.e., HR, $\dot{V}O_2$, power output) as it does not require specialized and expensive laboratory equipment. Given that RPE is anchored to subjective perceptions of exertion, this practical method of prescribing and monitoring exercise can auto correct for changes in CRF level. As CRF increases, exercise volume or absolute intensity must be increased to attain the same RPE levels, and this can be done without a formal assessment of CRF.



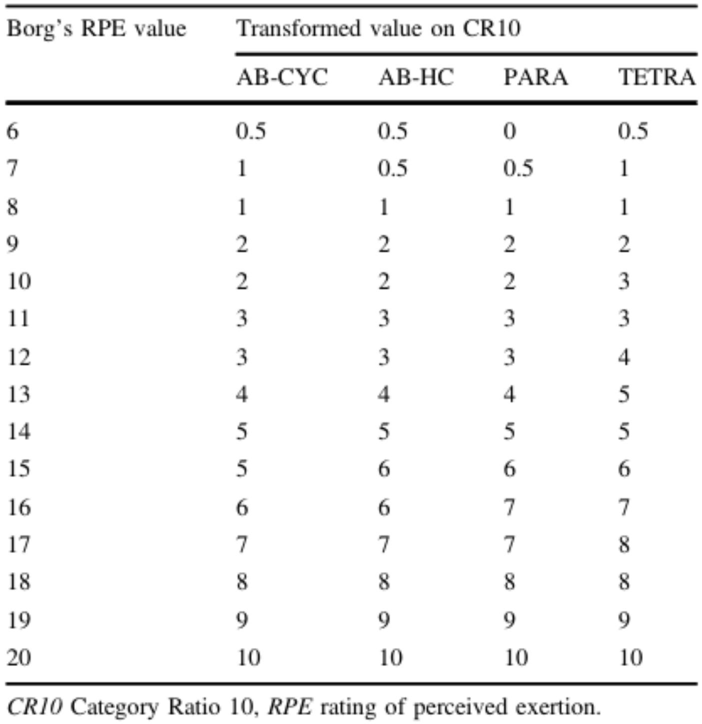
a)			b)		
	6			6	No exertion at all
	7	Very, very light		7	Extremely light
	8			8	
	9	Very light		9	Very light
	10			10	
	11	Fairly light		11	Light
	12			12	
	13	Somewhat hard		13	Somewhat hard
	14			14	
	15	Hard		15	Hard (heavy)
	16			16	
	17	Very hard		17	Very hard
	18			18	
	19	Very, very hard		19	Extremely hard
	20			20	Maximal exertion

Figure 1: a) the original (Borg, 1970) and b) updated (Borg, 1998) versions of Borg's 6-20 RPE scale. This figure is reprinted from Borg, 1998.



6-20 RPE Scale	CR-10
6	0.0
7	0.0
8	0.5
9	1.0
10	1.5
11	2.0
12	3.0
13	3.5
14	4.5
15	5.5
16	6.5
17	7.5
18	9.0
19	10.0
20	·

Figure 2: Transformation of values from Borg's RPE scale with corresponding value on the Category Ratio-10 (Borg & Ottoson, 1986). This figure is reprinted from Borg & Ottoson, 1986.



Borg's RPE value	Transformed value on CR10			
	AB-CYC	AB-HC	PARA	TETRA
6	0.5	0.5	0	0.5
7	1	0.5	0.5	1
8	1	1	1	1
9	2	2	2	2
10	2	2	2	3
11	3	3	3	3
12	3	3	3	4
13	4	4	4	5
14	5	5	5	5
15	5	6	6	6
16	6	6	7	7
17	7	7	7	8
18	8	8	8	8
19	9	9	9	9
20	10	10	10	10

CR10 Category Ratio 10, *RPE* rating of perceived exertion.

Figure 3: Transformation of Borg's 6-20 RPE scale and the proposed transformed values on the CR10 scale across multiple groups. This figure is reprinted from Hutchinson et al., 2021. Note. AB-CYC = able-bodied individuals using a leg cycle, AB-HC = able-bodied individuals using a hand-cycle. PARA = individuals with paraplegia using a hand-cycle, and TETRA = individuals with tetraplegia using a hand-cycle.

1.2.3 Ratings of perceived exertion and physiological markers of intensity

RPE is a promising tool for assessing exercise intensity in individuals with altered HR responses to physical stress (Williams et al., 2008). In the original development of the scale, Borg identified RPE to have a linear correlation with HR (Borg et al., 1987; B. J. Noble et al., 1983), and around this time, HR was found to be linearly correlated with $\dot{V}O_2$ (Bruce, 1984). Since these observations, RPE has been used to estimate percentage of $\dot{V}O_2$ in healthy non-disabled individuals (Borg, 1998). Conveniently, the 6-20 RPE scale can be transformed into HR with multiplication by 10 for young healthy, non-disabled adults (Borg, 1962). Before the widespread use of inexpensive and reliable HR monitors, exercise prescription was often based on RPE both during exercise testing and training (Scherr et al., 2013). In a study with 2560 healthy middle-aged adults RPE was strongly correlated with HR and blood lactate concentration ([BLa]) ($r>0.74$; $p<0.001$) during incremental exercise tests conducted on a treadmill or cycle ergometer (Scherr et al., 2013). RPE also correlates with oxygen uptake ($\dot{V}O_2$) (Wong et al., 2011), $\dot{V}O_2$peak (Coquart et al., 2014), and is strongly correlated to [BLa] (Dantas et al., 2015) in young healthy individuals. When performing 1hr long bouts of RPE-clamped cycling exercise, HR and respiratory frequency seem to be the most consistent physiological indicators of intensity, rather than $\dot{V}O_2$, respiratory exchange ratio (RER), and minute ventilation (V_E) (Cochrane-Snyman et al., 2019).

There is, a lack of understanding of the physiological determinants of RPE in individuals with an altered HR response, such as those with SCI. As described previously, individuals that have acquired an injury at the level of T6 or above will have blunted cardiovascular response to exercise due to altered innervation of the heart and often this corresponds to limb use (Krassioukov, 2009). Investigation of RPE during exercise testing in individuals with PP and TP has revealed a difference in $\dot{V}O_2$peak, HRpeak, [BLa]peak, however no difference in peak RPE response at the ventilatory threshold and respiratory compensation point between those with PP compared to TP (Leicht et al., 2014). For exercise testing, the use of Borg's RPE 6-20 scale has been used to monitor intensity for high fitness wheelchair athletes (Goosey-Tolfrey et al., 2010). When compared to traditional ramp-incremented exercise testing, perceptually-regulated exercise testing may be reliable, and more enjoyable for community-based manual wheelchair users (Hutchinson, Valentino, et al., 2019). Perceptually-regulated exercise testing has been demonstrated to have some validity, but more research is needed on the test-retest reliability of RPE in individuals with an SCI (Goosey-Tolfrey et al., 2010; van der Scheer et al., 2018). While RPE accurately predicts intensity in individuals with SCI (validity), there is only one study on the consistency to measure intensity (reliability) using RPE in individuals with an SCI, although it has promising applications for exercise programming in individuals with SCI (Stewart et al., 2000).

1.2.4 Application of ratings of perceived exertion for exercise prescription

RPE has practical benefits for use in exercise prescription, including ease of use, cost effectiveness, and automatic correction of intensity with changes in fitness (Parfitt et al., 2015). It is established that predictable time-dependent patterns emerge in healthy individuals during continuous exercise in each domain of $\dot{V}O_2$, RPE, HR, [BLa], minute ventilation, and ventilation frequency when monitored by constant power output (Dempsey, 1985; Gaesser & Poole, 1996; Garcin et al., 2008; Housh et al., 2000; Mielke et al., 2008). However, when maintaining a constant perceptual intensity, there are dissociations in metabolic, cardiovascular, respiratory, and neuromuscular parameters (Cochrane et al., 2015; Lander et al., 2009; Stoudemire et al., 1996). It has been shown that in specific conditions, RPE can be used in place of physiological measurements such as $\dot{V}O_2$ and [BLa] for the prescription of exercise in young healthy individuals (Dantas et al., 2015; Dunbar et al., 1991; Eston & Williams, 1988). Two studies have shown the relationship between RPE and HR or [BLa] are the same for both continuous and intermittent intensity exercise bouts (i.e., intervals) (Edwards et al., 1972; Zinoubi et al., 2018). However, as the duration of exercise lengthens, RPE becomes a less sustainable measure of exercise prescription at high intensities as compared to moderate intensity exercise prescription using RPE (Cochrane-Snyman et al., 2019). In one study, it was suggested that during an exercise bout that was RPE-guided, calibrated using an initial $\dot{V}O_2$peak test at 15% above the gas exchange threshold, runners dropped out of this high intensity domain after the first 14 minutes of exercise (Cochrane-Snyman et al., 2019). Therefore, RPE exercise prescription for high intensity may only be sustainable for 20 minutes or less, whereas RPE-guided exercise prescription for moderate intensity exercise can be maintained for 60 minutes of treadmill running, which may be mediated by breathing frequency as the only variable to track moderate and heavy intensity during RPE-clamped cycle ergometry (Cochrane et al., 2015). In support of this, in healthy non-disabled individuals perceptually regulated exercise training at an RPE of 13 seems to be enjoyable and increase CRF when performed in a supervised exercise training program (Parfitt et al., 2012). In a subsequent training study that involved 8 weeks of exercise at RPE 13 and RPE 15, only the RPE 13 group maintained their fitness at 6 months post-training (Parfitt et al., 2015). The researchers concluded that the RPE 15 group perceived themselves less competent during training and found the exercise intensity less pleasant leading to lower motivation in comparison to the RPE 13 group and therefore did not maintain their fitness at follow-up. Taken together, the available evidence suggests that RPE-guided exercise training interventions can improve fitness and generally appeals to motivational processes, however independent of training intensity, individuals with lower affective responses during exercise are less likely to maintain exercise behaviour.

For exercise interventions in individuals with SCI, studies have implemented RPE based exercise training of various intensities for exercise programs lasting up to 16 weeks in duration (Kim et al., 2015; Nooijen et al., 2015; Pelletier et al., 2013; Totosy de Zepetnek et al., 2015; Van Der Scheer et al., 2016), but only those prescribed at a moderate to vigorous intensity led to observed increases in $\dot{V}O_2$peak (Kim et al., 2015; Nooijen et al., 2015; Pelletier et al., 2015; Totosy de Zepetnek et al., 2015). To support RPE as a primary method of exercise intensity prescription for SCI, research examining the reliability and validity of RPE-guided training compared to HR-guided training remains to be conducted and further work defining changes in RPE over the course of an intervention is needed. Lack of consistency in the exercise modalities used, and inclusion of participants with varied fitness levels, in previous research limits the development of recommendations for use of RPE in exercise prescription and monitoring, particularly in participants with altered HR responses to exercise (van der Scheer et al., 2018).

1.2.5 Broader considerations of altered heart rate and ratings of perceived exertion

Many individuals are prescribed medications to medically manage symptoms of hypertension and cardiovascular disease, which reduce resting and exercise HR by 20-

30% (Lund-Johansen, 1983). After multiple medications and surgical interventions post- cardiac event, symptom-limited CPET is an important aspect of cardiac rehabilitation to inform exercise prescription designed to improve all-cause mortality risk (Lavie et al., 2009). Interestingly, the concept of perceptually-regulated exercise monitoring was first utilized to monitor severity of angina in patients with ischemic heart disease during exercise testing (Borg et al., 1980). Shortly after, the use of the RPE 6-20 scale became an exercise monitoring tool used during exercise training post-myocardial revascularization surgery (Gutmann et al., 1981). After six weeks of exercise-based cardiac rehabilitation, 20 male participants demonstrated higher MET levels at a given HR and RPE compared to pre-training levels. Forty years later, the clinical use of RPE to guide exercise prescription during cardiac rehabilitation exercise in coronary artery disease patients is common practice (Krieger et al., 2022). HR monitoring continues to be used in modern cardiac rehabilitation exercise settings, especially as HR monitors are now more affordable and used for tracking exercise easier than ever before. The replacement of HR with RPE is disputed for HIIT in cardiac rehabilitation, due to the underestimation of RPE and inaccuracy in meeting the target exercise intensity (Aamot et al., 2014; Whaley et al., 1997). In this previous work, RPE did not predict exercise intensity during cardiac rehabilitation in patients completing exercise (Aamot et al., 2014). Standardized instructions have been recommended prior to using RPE in exercise trials and the most recent review highlighted several methodological concerns associated with the use of RPE (Halperin & Emanuel, 2020). The relationship between RPE and exercise intensity cut points may be strengthened by a habituation session, also known as RPE familiarization, to improve the accuracy of

RPE as an exercise prescription method (Chen et al., 2002). Another method to aid in unifying the ways clinical populations interpret RPE is by using anchoring procedures that include connecting each level of the RPE to a certain experience (Bok et al., 2022).

It is uncontested that RPE can be variable and is dependent on multiple factors that are categorized into three umbrella terms pertaining to the internal factors, the perceptual continuum (e.g., mood, motivation), the physiological continuum (e.g., heart rate, lactate level, skin temperature), and the performance continuum (e.g., time, distance, exercise intensity) (Eston & Parfitt, 2007). The key challenges associated with using RPE for HIIT are underestimation of exercise intensity and bias associated with timing of when RPE is collected (Aamot et al., 2014; Bartlett et al., 2011; Foster et al., 2001; Green et al., 2007; Laurent et al., 2014). The use of RPE as an exercise prescription method for cardiac rehabilitation has previously resulted in exercise heart rate zones that are lower than the target heart rate zone for high intensity interval training in individuals in outpatient cardiac rehabilitation (Aamot et al., 2014), however in this study the RPE was averaged for all three intervals which may have affected the findings. The timing when participants are asked their RPE can also impact the rating they provide, whereby RPE typically increases with longer duration heavy exercise, termed perceptual drift (Bartlett et al., 2011; Foster et al., 2001; Green et al., 2007; Laurent et al., 2014). When considering the use of RPE for interval exercise, interval length may be an important consideration as previous research found that intervals 30 seconds in length mitigated the bias associated with perceptual drift that may occur during HIIT in non-disabled overweight men on a leg cycle (Kilpatrick et al., 2015). These issues associated with using RPE for HIIT have only been previously examined in non-disabled individuals, and should be considered when applied to research involving individuals with an SCI.

Novel research protocols have employed RPE as an exercise prescription method for stair climbing-based HIIT that has led to improvements in CRF (Dunford et al., 2021), however as described by Taylor and colleagues, there is a call to optimize cardiac rehabilitation with a focus on exercise intensity (Taylor, Bonikowske, et al., 2021). In recent review, attendance to HIIT in the US was high and comparable to MICT (Taylor, Holland, et al., 2021). In the UK cardiac rehabilitation database, HIIT was more effective for health outcomes, including greater gains of quality of life after 12 months, and cost effective compared to MICT (Albustami et al., 2023). As cardiac rehabilitation outpatient services in Canada are increasingly community-based, home-based, or even virtually delivered (Babu et al., 2020), it is important to investigate low cost, simple, and effective methods of exercise prescription for individuals with coronary artery disease.

1.2.6 Psychological considerations of using ratings of perceived exertion

Use of RPE guided exercise prescription may provide additional benefits to long term exercise adherence, such as the benefits associated with allowance for self-directed exercise intensity at each RPE level (Parfitt et al., 2015). The relationship between self-directed exercise intensity, affect, and exercise adherence has been demonstrated in non-disabled individuals and is rooted in a theoretical basis. Studies with participants either given the option to choose their exercise intensity (self-selected) or not (imposed) conditions, demonstrated more positive affect in self-selected conditions (Hamlyn-Williams et al., 2014; Rose & Parfitt, 2007). In a study without a control group, a training intervention of 4 weeks and RPE-guided intensity protocol at

RPE 13 was perceived as positive throughout, determined by a Feeling Scale rating of 3±1 (mean±SD) (Hardy & Rejeski, 1989; Parfitt et al., 2012). In addition, self-paced exercise has been found as physically less challenging (Lander et al., 2009) and perceptually-regulated exercise testing is reliable and results in more positive affect in individuals with SCI (Hutchinson, MacDonald, et al., 2019). According to self-determination theory (Deci & Ryan, 1985), the three psychological needs, 1) autonomy, 2) competence, and 3) relatedness, are required to support the development of intrinsic motivation and the first two can be met through the use of RPE (Parfitt et al., 2015). Using this theory, RPE may increase intrinsic motivation and there is some indication that intrinsic motivation is especially important for long-term exercise program adherence and therefore maintenance (Teixeira et al., 2012). Given that exercise training interventions are often designed without considerations for behaviour change frameworks, perhaps this impact of using RPE as an exercise prescription tool is the greatest strength.

1.3 Knowledge gaps and objectives

Significant knowledge gaps in the literature remain to be explored. The implementation of RPE for HIIT exercise prescription and monitoring in individuals with altered HR responses to exercise is limited by the current lack of understanding of the physiological responses to RPE-guided exercise training. There are no studies examining the use of RPE-guided exercise training interventions in comparison to an intensity-matched training group in both a supervised and unsupervised settings. Additionally, it has been suggested that future studies need to optimize the duration, intensity, and volume of HIIT in individuals with SCI. The experimental projects of this PhD program will address these three knowledge gaps:

- **Knowledge gap 1:** The high level of heterogeneity existing in the currently available research on perceptually regulated exercise training in individuals with SCI limits the application of this research (e.g., training modality, research outcomes, and population characteristics). Primary research in this area has yet to be evaluated and summarized to guide future practice.
- **Knowledge gap 2:** There is a lack of understanding of the physiological regulation of RPE during exercise in individuals with altered HR responses to exercise, which limits the implementation of RPE as a HIIT exercise prescription tool in these populations.
- **Knowledge gap 3:** No research has been conducted on the effectiveness of a perceptually regulated HIIT arm cycling exercise in both non-impaired and mobility-impaired individuals due to SCI (Parfitt et al., 2015).

The aims of this PhD thesis are as follows:

- **Aim 1**: To synthesize and appraise previous research using RPE as the primary method of prescription for exercise intensity during exercise training across a spectrum of health and disease through a systematic review.
- **Aim 2:** To study the relationships between physiological predictors of RPE during leg cycling exercise to maximum capacity in individuals referred for clinical cardiopulmonary exercise testing.

- **Aim 3:** To explore the perceptions of and experiences with exercise intensity, particularly high intensity, for individuals with a traumatic spinal cord injury and their healthcare professionals.
- **Aim 4:** To evaluate the relationships between physiological and psychological variables that may contribute to ratings of perceived exertion during arm cycling exercise in mobility impaired individuals with SCI and non-impaired individuals.

This thesis includes the following chapters:

- **Chapter 2:** Effects of perceptually regulated exercise training on cardiorespiratory fitness and peak power output in adults with spinal cord injury: a systematic review and meta-analysis.
- **Chapter 3:** Leg muscle strength and power predict ratings of perceived effort during cardiopulmonary exercise testing.
- **Chapter 4:** Exploring the patient and healthcare professional perspectives of using ratings of perceived exertion during rehabilitation for exercise after a spinal cord injury.
- **Chapter 5:** Arm strength and age predicts central ratings of perceived exertion during arm cycling exercise in those with a spinal cord injury.

1.4 Relevance

Because of decreasing length of rehabilitation stays, the health care system is becoming increasingly reliant on outpatient services for the continued care of persons with SCI and coronary artery disease (Craven et al., 2012; Ottenbacher et al., 2004;

Polyzotis et al., 2012; Whiteneck et al., 2011). Despite established benefits of exercise, there is currently very limited infrastructure in place for long-term services or resources available to prescribe and assess exercise intensity in a home-based setting (Craven et al., 2012). Home-based programming is becoming an increasingly common choice for many patients (Clark et al., 2015) and virtual modes of delivery may even become regular practice as a result of the social distancing practices that are required during COVID-19 (Babu et al., 2020). The research in this thesis will inform the use of RPE as an accessible and reliable exercise intensity prescription method for HIIT in those with altered HR responses to exercise. Implementation of RPE guided HIIT exercise in supervised settings, such as in-patient rehabilitation, for individuals taking HR altering medications for coronary artery disease and those with SCI may lead to better exercise adherence long after the cessation of supervised exercise programming. In the long-term, patients with an altered HR response to exercise may feel more confident in the use of this method through self-guided exercise in a community setting. In the future, RPE-guided HIIT exercise could also be incorporated into the physical activity guidelines for individuals with altered HR responses to exercise.

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REVIEW ARTICLE (META-ANALYSIS)

Effects of Perceptually Regulated Exercise Training on Cardiorespiratory Fitness and Peak Power Output in Adults With Spinal Cord Injury: A Systematic Review and Meta-analysis

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Abstract

Objective: To analyze and summarize the effect of regulating exercise training interventions with subjective measures of intensity on cardiorespiratory fitness, measured by peak oxygen uptake ($\dot{V}O_{2peak}$) and peak power output (PO_{peak}) in adults with spinal cord injury (SCI).

Data Sources: Four databases (MEDLINE, Embase, PsycINFO, SPORTDiscus) were searched from inception up until September 1, 2020, and updated November 18, 2021.

Study Selection: Searches combined keywords relating to the topics: SCI, subjective measures of exercise intensity, and exercise.

Data Extraction: Two reviewers independently conducted eligibility screening, data extraction, and assessed the risk of bias. Nine studies were included in the systematic review and meta-analysis, resulting in the inclusion of data from 95 adults with SCI representing both sexes and a diverse range of age, time since injury, lesion level, and lesion completeness classifications.

Data Synthesis: Data were extracted and added to summary tables with 3 outcomes: $\dot{V}O_{2peak}$, PO_{peak}, and Other. Mean and SD values for $\dot{V}O_{2peak}$ and PO_{peak} were extracted from pre- and post-perceptually regulated exercise training.

Conclusions: All studies used ratings of perceived exertion scale to prescribe exercise intensity. Seven of 8 studies concluded an improvement in $\dot{V}O_{2peak}$, and 5 studies of 7 concluded an improvement in PO_{peak}. In the outcome *Other*, 5 studies concluded an improvement, and 3 studies concluded no change. There was evidence for an improvement in cardiorespiratory fitness, measured by $\dot{V}O_{2peak}$ and PO_{peak} after perceptually regulated exercise training in adults with SCI (Grading of Recommendations, Assessment, Development, and Evaluation ratings: *Low*) (mean difference [MD], 2.92mL/kg/min; 95% confidence interval [CI], 1.30-4.54; P=.0004 and MD, 9.8W; 95% CI, 5.5-14.3; P<.0001, respectively). This review provides critically appraised, cumulative evidence on the use of perceptually regulated exercise training in individuals with SCI.

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Worldwide between ~600,000 and 940,000 people incur a traumatic spinal cord injury (SCI) per year.[1] Individuals with SCI are among the lowest on the physical activity participation spectrum[2-4] and are particularly vulnerable to inactivity-related diseases (e.g., cardiovascular disease, diabetes mellitus). Participation in exercise and sports have been shown to improve the physical health and psychological well-being of individuals with SCI.[5] Previously, people with disability were rarely the focus of physical activity promotion[4]; however, the development of the SCI-specific exercise guidelines has been an international effort.[6] The exercise guidelines for individuals with SCI indicate that 2 sessions of at least 20 minutes of moderate to vigorous aerobic exercise per week and 2 sessions of strength training exercise for each major functioning muscle group are necessary to receive cardiorespiratory fitness benefits.[6]

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Given the multitude of physical and psychological barriers individuals with SCI face,[7] implementation of exercise into the everyday lives of individuals with SCI remains a challenge. Within this, prescribing and monitoring exercise intensity poses its own difficulties, particularly for individuals with an altered heart rate response to exercise. The available methods to assess exercise intensity often require specialized laboratory equipment.[8] In addition, exercise intensity prescription and monitoring can be limited by both physiological and practical limitations with SCI. Exercise intensity prescription and monitoring based on heart rate for individuals with SCI is affected by a nonlinear relationship between heart rate and workload,[9] and the cardiovascular response to exercise will be blunted in an individual with complete SCI above T6.[10] This exercise response is further characterized by decreased vasoconstriction below the level of injury, decreased venous return, lower stroke volume, and decreased maximum heart rate.[10] Additionally, there is evidence to show that an SCI of any level, as well as autonomic completeness of the SCI, may alter the balance of autonomic function and cardiovascular function.[10]

Given the limitation of objective measures for monitoring exercise training in SCI, an alternative could be to use perceptual measures of exercise intensity. Such measures, including ratings of perceived exertion (RPE), are commonly used in a variety of inpatient exercise rehabilitation and wheelchair sport training settings. This occurs despite no cumulative evidence showing that perceptually regulated training leads to improvements in cardiorespiratory fitness, as well as a lack of understanding of the physiological underpinnings of RPE in individuals with SCI.[11,12] Cardiorespiratory fitness, measured by peak oxygen uptake ($\dot{V}O_{2peak}$) during a graded exercise test, is commonly used to monitor the effect of exercise rehabilitation interventions on an individual level.[13] Alternatively, peak power output (PO_{peak}) is a complimentary assessment that can also indicate change in physical fitness and is predominantly determined by level of injury, training status, sex, and body mass index.[14] For individuals with SCI, increased fitness levels can reduce physical strain during standardized tasks associated with activities of daily life, such as wheeling and transfers,[15-17] and increase quality of life.[5]

With the aim of informing exercise training prescription, the objective of this review was to examine the effect of regulating exercise training with a subjective measure of intensity on cardiorespiratory fitness, measured by $\dot{V}O_{2peak}$ and PO_{peak} in adults with SCI.

Methods

This review was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analyses guidelines.[18] The review protocol was registered with the International prospective register of systematic reviews (PROSPERO), registration number CRD42020210552. All supplemental appendices are publicly available on a research data repository (https://doi.org/10.5683/SP3/PHKZQR).

List of abbreviations:

CI	**confidence interval**
CR10	**Category Ratio 10**
GRADE	**Grading of Recommendations, Assessment, Development, and Evaluation**
MD	**mean difference**
PO_{peak}	**peak power output**
RPE	**rating of perceived exertion**
RoB 2.0	**Risk of Bias 2.0**
SCI	**spinal cord injury**
$\dot{V}O_{2peak}$	**peak oxygen uptake**

Study eligibility

Based on previous systematic review eligibility criteria in this field of research[5,19] and consultation with an independent librarian, the eligibility criteria were determined for this systematic review. Original studies of any design were included that met the following criteria: (1) greater than 50% of the sample being adults (aged 16 years or older) with traumatic or nontraumatic SCI, excluding those with progressive disease such as multiple sclerosis or congenital condition such as spina bifida; (2) minimum 2-week exercise training or physical activity intervention with at least 2 sessions of perceptually regulated exercise total; (3) outcome measure of cardiorespiratory fitness (measured by $\dot{V}O_{2peak}$) and/or PO_{peak}; and (4) peer-reviewed original research published in English, not reviews (i.e., narrative, systematic, scoping), case studies, commentaries, and conference abstracts.

Eligibility screening

Two reviewers (S.V., M.J.H.) independently conducted eligibility screening using Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia).[a] Differences at both the title and/or abstract screening and full-text review were discussed between reviewers to agree consensus. Titles and/or abstracts that clearly did not meet the eligibility criteria were excluded, while reasons for excluding articles on full-text review were recorded.

Information sources

MEDLINE, Embase, PsycINFO and SPORTDiscus were searched from inception up until first September 2020 and updated up until November 18, 2021. The search strategy was developed in consultation with an independent librarian and research team. Searches combined keywords relating to SCI (e.g., tetraplegia, spinal cord lesion, spine impairment), perceptual measures of exercise intensity (eg, perceived exertion, RPE), and exercise training (e.g., cardiorespiratory fitness, strength, resistance, physical activity). The Boolean term *OR* was used between words of the same topic, with *AND* used to combine the 3 topics. No additional limiters were used. Any studies that included data from animal models only were filtered as an additional line of the search strategy. The individuals involved with this review were only able to include articles written in English; however it is anticipated that there was a limited effect of this restriction on our conclusions.[20] A sample search strategy for Embase can be found in appendix 1.

Data extraction

The same 2 authors also performed independent data extraction on each included study. The following data were extracted from each study: author(s) and publication year; study design; sample size; participant characteristics; setting; details of the intervention (e.g., number of weeks, sessions per week, duration of sessions); details of the perceptually regulated aspect of training (e.g., RPE scale used, target intensity); cardiorespiratory fitness outcomes (including $\dot{V}O_{2peak}$, PO_{peak}); adherence to training; adverse events; and all reported outcomes that did not fit within an aforementioned category were extracted into the category *Other*. If original data were unable to be extracted from tables, the data in figures were extracted using the online software WebPlotDigitizer,[b] otherwise the data not reported were noted.

Synthesis of evidence

All data were extracted in the format which it was presented. In some cases, $\dot{V}O_{2peak}$ was converted from L/min to mL/kg/min on an individual basis where the data were available. When using median and IQR, mean was estimated as median and IQR was converted to SD using the formula SD=IQR/1.35.[21]

For the systematic review, to be deemed an *Improvement* in the outcomes, there must have been statistically significant improvements and the majority of participants must have had an increase in that outcome. *No change* indicates that there was mostly no change in the outcome variable. *Inconclusive* indicates that there was inconclusive evidence to suggest an improvement or no change in the outcomes, usually composed of increasing and decreasing outcomes between participants.

Quality of evidence assessment (risk of bias) and certainty assessment (Grading of Recommendations, Assessment, Development, and Evaluation)

Two reviewers (S.V., M.J.H.) also independently assessed the risk of bias for each study. Randomized controlled trials were assessed using the Cochrane Risk of Bias 2.0 Tool (appendix 2.1), with nonrandomized trials assesses using Cochrane Risk of Bias in Nonrandomized Studies of Interventions tool (see appendix 2.2).[22,23] For all other study designs, risk of bias was assessed using the modified Downs and Black scale (see appendix 2.3).[24,25] Similar to previous systematic reviews with populations with SCI, studies were then qualified as level 1, 2, 3, or 4 according to table 1.[25,26] The Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) framework[27] was used to assess and assign a confidence rating to the body of evidence (appendices 3.1 and 3.2). Evidence was assessed for *risk of bias, inconsistency, imprecision, indirectness*, and *publication bias*.[27] The body of evidence began with a rating of *High* with a stepwise downgrading to *Moderate, Low*, or *Very low* depending on the study design and any additional downgrading for the existence of any of the 5 aforementioned factors (appendix 4).[27]

Data analysis

The meta-analyses were performed using Review Manager.[c] Meta-analyses were conducted to pool studies with similar comparisons and outcome measures (e.g., $\dot{V}O_{2peak}$), with mean difference (MD) calculated. The outcome variables included MD in $\dot{V}O_{2peak}$ and PO_{peak} before and after perceptually regulated exercise intervention in adults with SCI. A secondary meta-analysis was conducted using MD to compare perceptually regulated exercise training with a control group.

Each MD was weighted according to the inverse variance method and pooled with a random-effects model. The MD summary statistic was chosen over a standardized MD statistic given that the outcome variable methodologies are similarly assessed between studies. A positive MD corresponded with an increase in $\dot{V}O_{2peak}$ (mL/kg/min) or PO_{peak} (W). Heterogeneity was considered high when I^2 was ≥50%.

Results

Search process

The search identified 319 articles, while eligibility screening led to the inclusion of 10 articles, composed of 9 studies without duplicate samples (fig 1).[28-36] For the duplicate studies, the study with the larger sample size was used for the purpose of the meta-

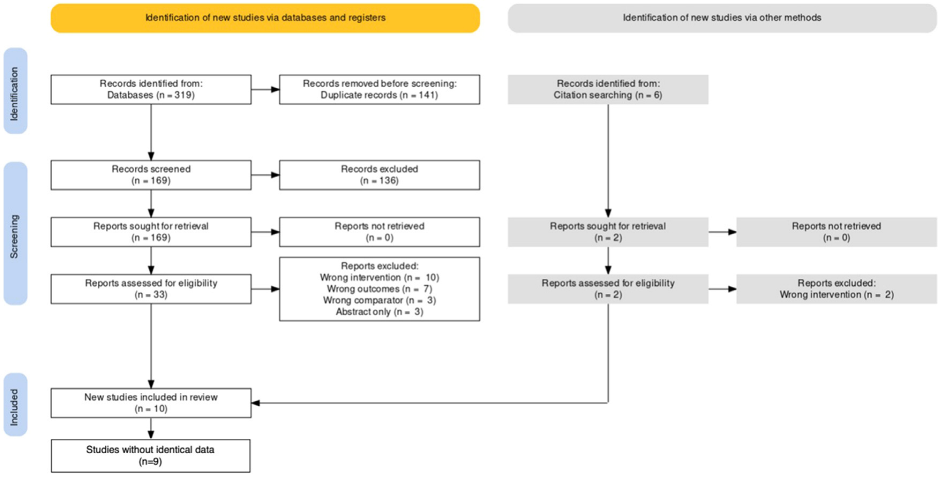

Fig 1 PRISMA flowchart of the literature search and selection process of the eligible articles. Created using PRISMA2020: R package and ShinyApp (Version 0.0.2) and Microsoft Powerpoint (Version 16.55). Abbreviation: PRISMA, Preferred Reporting Items for Systematic Review and Meta-Analyses.

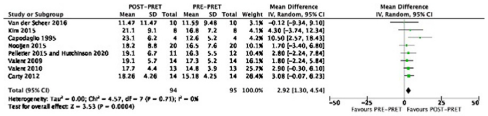

Fig 2 Forest plot for the effects of perceptually regulated training, compared with pretraining, on peak oxygen uptake. Abbreviations: CI, confidence interval; IV, inverse variance; PRET, perceptually regulated exercise training.

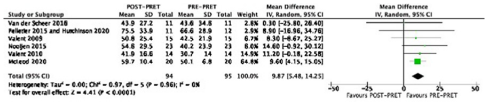

Fig 3 Forest plot for the effects of perceptually regulated training, compared with pretraining, on peak power output. Abbreviations: CI, confidence interval; IV, inverse variance; PRET, perceptually regulated exercise training.

analysis; however, throughout the review they are cited together to ensure both citations were captured.[28,33] The research articles included 5 control trials and 4 prospective cohort studies that were included in the meta-analysis comparing pre- and postperceptually regulated training (table 2, figs 2 and 3). A total of 3 studies were identified as randomized controlled trials with a habitually active group for comparison and were included in the secondary meta-analysis (figs 4 and 5).[28,32,33,37] These 3 studies described their habitually active groups as "continuation of usual activities,"[32] "active control,"[28] and "not offered any intervention." All 3 studies recruited their participants using databases of rehabilitation centers and SCI patient organizations,[37] advertisements at local community organizations,[28,33] or not reported.[32] Two studies with control groups were not included in the secondary meta-analysis because of methodological differences. One randomized controlled trial compared 2 groups of different exercise intensities within the first 6 months of SCI,[35] and 1 prospective cohort study included a retrospective age-, sex-, and lesion level−matched control group.[31] The reference list, complete data extraction table, and a sample literature search can be found on the repository website (https://doi.org/10.5683/SP3/PHKZQR).

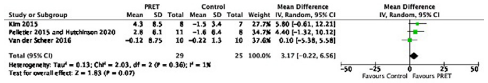

Fig 4 Forest plot for the effect of perceptually regulated exercise training, compared with control group, on peak oxygen uptake. Abbreviations: CI, confidence interval; IV, inverse variance; PRET, perceptually regulated exercise training.

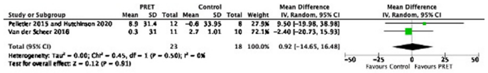

Fig 5 Forest plot for the effect of perceptually regulated exercise training, compared with control group, on peak power output. Abbreviations: CI, confidence interval; IV, inverse variance; PRET, perceptually regulated exercise training.

A criterion for the articles included in this review required studies to use any perceptual scale as a method of exercise prescription. There were 4 studies that were eligible at title and abstract screening; however, they were eliminated during full-text screening because of alternate methods of exercise prescription or monitoring such as percentage heart rate.[14,38-40] In these studies that were not captured in the review, perceptual measures may have been measured after the training session or as a secondary to other measures of exercise intensity.

Characteristics of included studies

Participant characteristics in the eligible studies are included in table 2, including a total of 159 (134 male and 25 female) participants with a mean age of 42±7 years, a range of lesion levels (C2-L5), American Spinal Injury Association Impairment Scale classification scores (A-D), and mean time since injury of 6 years. Two studies indicated participants were taking heart rate−reducing medications, and the other 7 studies did not report the medication status of their participants. Based on the exclusion criteria, 6 studies required participants to be medically stable and without cardiovascular disease. The training status of the study recruitment criteria was mostly untrained (n= 4); however, some were trained (n=2) with others not reported (n=2). Data from the exercise interventions and main findings of the studies are included in table 3. The exercise interventions in the 9 studies occurred in either a rehabilitation center or hospital setting (n=6) or at home (n=3). The studies were conducted in the Netherlands (n=4), Canada (n=3), Korea (n=1), and Italy (n=1).

The average frequency of exercise sessions per week was 3±1 times per week (range, 2-5 times/wk). Of the studies included, 8 studies used the Category Ratio 10 (CR10) scale, and 2 studies used the 6-20 scale (see Exercise Prescription column of table 2). After converting all RPE prescriptions to the CR10 scale, the average overall perception used to prescribe exercise was 5 of 10 for the 9 studies included. The RPEs used to prescribe exercise were 2 of 10 to characterize light (n=2 studies), 3-5 of 10 to characterize moderate (n=2 studies), and 6-7 to characterize hard/vigorous (n=3 studies). Of the 9 studies, 1 study used a light-, moderate-, and high-intensity prescription depending on the day of the week, which stayed consistent throughout the training intervention, and 2 studies used progression (e.g., increase of 1 RPE for prescription) throughout the exercise training intervention. Only 1 journal article used standardized instructions (n=5 not reported), and 3 studies used RPE familiarization in their study design (n=5 not reported). RPE was monitored and supervised by various methods, including by exercise trainer (n=1), sport therapist (n=1), and trained paramedical research assistant (n=1). Five studies did not report the level of exercise training supervision, however, given that 4 studies were likely supervised and 1 study was likely unsupervised based on the location of training indicated. The level of training or familiarization of the individual supervising RPE was not reported in any study.

The average time of exercise sessions were 38±16 minutes in length (range, 10-60 minutes). Participants captured in this review exercised for an exercise intervention duration of 10±5 weeks (range, 5-39 weeks). The exercise modalities used included arm cycle ergometry (n=7), wheelchair propulsion on a treadmill (n=1), a hybrid recumbent stepper (n=1), and electrical stimulation (n=1).

Table 1 Eligible study designs and criteria for classifying the level of evidence for individual studies

Level of Evidence[*]	Study Design	Cutoff Quality Score[†]	Description Study Design
Level 1 study	Randomized controlled trial	Rating of *Low* using RoB 2.0	Using within-participants comparison with randomized conditions or crossover designs
Level 2 study	Randomized controlled trial	Rating of *High* or *Some Concerns* using RoB 2.0	See above
	Nonrandomized controlled trial	Rating of *Low* or *Moderate* using ROBINS-I	Comparing intervention vs control groups (not randomly allocated)
	Prospective cohort study	Downs & Black score ≥21	Longitudinally comparing at least 2 similar groups with 1 exposed to an intervention
Level 3 study	Nonrandomized controlled trial	Rating of *Moderate/Serious/ Critical/NI* using ROBINS-I	See above
	Prospective cohort study	Downs & Black score <21	See above
	Retrospective cohort study	Downs & Black score ≥21	Retrospectively comparing an intervention group with a historical control group
	Pre-post study	Downs & Black score ≥21	Using a baseline measure, intervention, and a posttest in a single group
Level 4 study	Retrospective cohort study	Downs & Black score <21	See above
	Pre-post study	Downs & Black score <21	See above

Abbreviations: RoB 2.0, Risk of Bias 2.0 tool; ROBINS-I, Cochrane Risk of Bias in Nonrandomized Studies of Interventions.

[*] Level 1 studies were considered to contain the least risk of bias. A Level 1 study was defined as a high-quality randomized controlled trial, receiving a Low risk of bias from either the RoB 2.0 or ROBINS-I tool.[1,2] Level 2 studies were lower-quality randomized controlled trials and higher-quality nonrandomized controlled trials and prospective cohort studies, which were defined by ROBINS-I[2] *Low* risk of bias and Downs & Black score of 21 or higher (upper quartile of the maximum score of 28).[3,4] Similarly, Level 3 studies were lower-quality nonrandomized controlled trials and prospective cohort studies as well as higher-quality pre-post studies and retrospective cohort studies.

[†] The quality checklist used to assess the randomized controlled trials was the Cochrane RoB 2.0 tool.[1] Nonrandomized controlled trials were assessed using the Cochrane Risk of Bias in Nonrandomized Studies of Interventions tool.[2] All other studies were assessed with a modified version of the Downs and Black scale, which ranges from 0-28 points.[3,4] For more information on the modified Downs and Black scale, see references.[5,6]

Risk of bias of individual studies

Each of the 9 studies was classified for its individual level of evidence in accordance with table 1. Three were classified as level 1 studies, 4 as level 2 studies, and 2 as level 4 studies (see table 2). Four studies used a randomized controlled trial design, with Risk of Bias 2.0 scores of *Low* risk of bias. Two studies used a nonrandomized controlled trial design, with risk Cochrane Risk of Bias in Nonrandomized Studies of Interventions I scores of a *Moderate* risk of bias. Three studies used a prospective cohort trial design and were scored 14, 21, and 21 using the Down and Black tool. The complete risk of bias scoring tools for each checklist item of the studies can be found on the data repository (https://doi.org/10.5683/SP3/A6O5KH).

Outcomes

The main outcome measures analyzing cardiorespiratory fitness included $\dot{V}O_{2peak}$ (n=2) and PO_{peak} (n=1) or both (n=6). Some studies reported on other outcomes including endurance capacity, peak heart rate, muscle strength, session RPE, enjoyment, and pain. Of the 8 studies that reported on $\dot{V}O_{2peak}$, 7 studies reported an improvement after the perceptually regulated exercise intervention,[28-33,36] and 1 study reported no change.[37] The study that reported no change also had the lowest intensity exercise prescription and there was no change in the control group, which was described as “inactive, community-dwelling manual wheelchair users with long-term SCI"[37(p34)] that were "not offered any intervention.”[37(p34)] Of the 7 studies that reported on PO_{peak}, 5 studies reported an improvement after the perceptually regulated exercise intervention,[28,30,31,33-35] and 2 studies reported no change.[36,37] Of the 8 studies that reported on *Other* outcomes, 5 reported an improvement, and 3 studies reported no change (see table 3 for details).

$\dot{V}O_{2peak}$ and PO_{peak} improved after exercise interventions prescribed by perceptual measures of intensity, (MD, 2.92mL/kg/min; 95% confidence interval [CI], 1.30-4.54; *P*=.0004 and MD, 9.8W; 95% CI, 5.5-14.3; *P*<.0001, respectively) (GRADE ratings: *Low*) (see figs 2 and 3).

When comparing perceptually regulated exercise training with a control intervention, $\dot{V}O_{2peak}$ and PO_{peak} did not change (MD, 3.17mL/kg/min; 95% CI, −0.22 to 6.56; *P*=.07 and MD, 0.92W; 95% CI, −14.65 to 16.48; *P*=.91, respectively) (GRADE ratings: *Low*) (see figs 4 and 5).

Evidence appraisal using GRADE

For the first 2 comparisons examining pre- to postperceptually regulated training on the outcomes $\dot{V}O_{2peak}$ and PO_{peak}, all studies included were classified as pre-post observational studies. According to the GRADE scoring criteria observational studies began with a *Low* certainty assessment. The GRADE assessment revealed there was no additional evidence of *risk of bias, inconsistency, imprecision*, or *other considerations* that may alter the certainty assessment. The evidence for improvement in $\dot{V}O_{2peak}$ and PO_{peak} for any adult with SCI were both classified as *Low* certainty according to the GRADE assessment (see appendix 3.1).

Two exploratory meta-analyses examined perceptually regulated exercise training compared with a control group on $\dot{V}O_{2peak}$ and PO_{peak} and included only randomized controlled trials. The randomized controlled trial study design began with a *Moderate* certainty assessment, according to the GRADE scoring criteria. There was evidence of *imprecision* because of the 95% CI crossing over the no effect line in both analyses. Therefore, the GRADE certainty in the evidence for augmented cardiorespiratory fitness,

Table 2 Study participants

Study Reference and Quality Score	N (Men/Women)	Training Status	Age (y), Mean (Range)	Time Since Injury, Mean ± SD (Range)	AIS Classification
Capodaglio et al[36] Level 2 ROBINS-I=Moderate risk of bias	4 (4/0)	NR	32 (19-45)	3.2 mo ± NR (NR)	NR
Carty et al[29] Level 2 Downs & Black=21	14 (11/3)	Sedentary	45 (29-54)	11±11 y (0.3-42y)	A=11 B=3
Kim et al[32] Level 1 RoB 2.0=Low risk of bias	8 (6/2)	Untrained; had not exercise regularly during the 6 mo preceding the study	32 (22-29)	5±3.2 y	A=7 B=8
McLeod et al[35] Level 2 RoB 2.0=Low risk of bias	20 (15/5)	NR	45 (NR)	MICT: 1.9±1.4 d[35] SIT: 2.4±2.3 d	A=2 C=8 D=10
Nooijen et al[34] Level 4 Downs & Black = 14	45 (39/6)	Trained (last 8wk of inpatient rehabilitation)	44 (30-50)	4.3±2.0 mo (IQR, 3.0-5.8mo)	NR; 64% had motor complete lesions
Pelletier et al[28] & Hutchinson et al[33] Level 1 RoB 2.0=Low risk of bias	11 (11/0)	NR	40 (25-56)	15±8.5 y (1-36y)	A=2 B=2 C=7 D=1
Valent et al[30] Level 4 Downs & Black=21	15 (12/3)	Physically active	38 (22-64)	10±7.6 y	A=2 B=10 C=1 D=2
Valent et al[31] Level 2 ROBINS-I=Moderate risk of bias	17 (13/4)	Untrained	46 (22-65)	3 mo or less	A/B=11 C/D=6
van der Scheer et al[37] Level 1 RoB 2.0=Low risk of bias	14 (12/2)	Untrained	55 (42-64)	16 y (IQR, 13-29y)	A=9 B=1 C=4 D=4

Abbreviations: AIS, American Spinal Injury Association Impairment Scale; MICT, moderate intensity continuous training; NR, not reported; RoB 2.0, Risk of Bias 2.0 tool; ROBINS-I, Risk of Bias in Nonrandomized Studies of Interventions; SIT, sprint interval training.

Table 3 Simplified data extraction of the included studies

Study Reference and Quality Score	Study Design	Comparison	Intervention Setting	Exercise Prescription	Standardized Instructions	RPE Familiarization	$\dot{V}O_{2peak}$	PO_{peak} and Workload	Other
Capodaglio et al[36] Level 2	Nonrandomized controlled trial	EXP: ACE CON: Conventional rehabilitation	Hospital rehabilitation center	Duration: 6 wk Frequency: 5 × /wk	NR	Yes (familiarization with scale and 15-min endurance tests)	Improvement: ↑$\dot{V}O_2$ values (62.6%) in Group A at post-training	No change: ↔Workload exerted (kpm) at posttraining in both groups	Improvement: ↑Endurance capacity in Group A (iso perception curve was shifted far beyond confidence limits generated by the standard error of the estimate of pre-training)
ROBINS-I=Moderate risk of bias				Intensity: 2-7/10 RPE using CR10 scale Time: 20-30 min Progression: NR					None reached RER>1 (moderate effort)
Carty et al[29]	Prospective cohort study	EXP: NMES-rowing/ NMES-ACE/NMES lower crank ergometry	Home-based training	Duration: 8 wk	No	Yes	Improvement:	NR	Improvement:
Level 2		CON: none		Frequency: 5 × /wk			↑$\dot{V}O_{2peak}$ (n=13 of 14, ~22.65%)		↑HR_{peak} (n=9 of 11, ~2.63%)
Downs & Black=21				Intensity: 13-15/20 RPE using 6-20 scale Time: 60 min Progression: NR					
Kim et al[32] Level 1	Randomized controlled trial	EXP: ACE CON: Chronic SCI continuation of usual activities	Outpatient rehabilitation center	Duration: 6 wk Frequency: 3 × /wk	No	No	Improvement: ↑$\dot{V}O_{2peak\ in\ EXP\ group}$ and ↓$\dot{V}O_{2peak}$ in CON group	NR	Improvement: ↓BMI and waist circumference in the EXP group
RoB 2.0=Low risk of bias				Intensity: 5.6, 7/10 RPE using CR10 scale Time: 20-30 min Progression: intensity+1 RPE per 2 wk					↑Muscle strength (all upper body) in EXP group ↓Muscle strength in CON group ↑HDL-C in EXP group ↓HOMA-IR in EXP group ↓Insulin in the EXP group
McLeod et al[35] Level 2	Randomized controlled trial	EXP: SIT-ACE CON: MICT-ACE	Inpatient rehabilitation	Duration: 5 wk Frequency: 3 × /wk	No	Yes (Toronto Arm Crank Protocol)	NR	Improvement: ↑$PO_{peak\ in\ both\ groups}$	No change: ↔ Enjoyment, exercise self-efficacy, pain in both groups
RoB 2.0=Low risk of bias				Intensity: 16/20 peripheral RPE for SIT, 12/20 peripheral RPE for MICT, both using 6-20 scale Time: 10 min for SIT, 25 min for MICT Progression: NR				↑% $PO_{peak\ in\ both\ groups}$	Trend for lower peak HR in tetraplegia vs paraplegia
Nooijen et al[34]	Prospective cohort Study	EXP: ACE Interval training	Rehabilitation center (4 locations)	Duration: 8 wk	NR	NR	Improvement:	Improvement:	NR
Level 4 Downs & Black=14		CON: None		Frequency: 3 × /wk Intensity: 4-7/10 RPE using CR10 scale Time: 45-60 min Progression: NR			↑$\dot{V}O_{2peak}$ (~9.6%) ↑$\dot{V}O_{2peak}$/kg body mass (~9.9%)	↑PO_{peak} (~36.4%) ↑PO_{peak}/kg body mass (~27.2%)	
Pelletier et al[28] & Hutchinson et al[33] Level 1	Randomized controlled trial	EXP: ACE or hybrid recumbent stepper CON: Active control group	Community exercise facility	Duration: 16 wk Frequency: 2 × /wk	NR	NR	Improvement: ↑$\dot{V}O_{2peak}$ (~9.6%) in EXP group & ↓in CON group (~5.4%)	Improvement: ↑Submaximal power output (~26.3%) in EXP group	Improvement: ↑Strength (~11.5%-38.9% depending on muscle group) in EXP group & ↔ in cCON group (~-3.8 to +3.9%)
RoB 2.0=Low risk of bias				Intensity: 3-6/10 RPE using CR10 scale Time: 20 min			↑$\dot{V}O_{2peak}$/kg body mass (~17.1%) in EXP group & ↓in CON group (~9.0%) ↑(~9.6%) & ↓in CON group	↑ PO_{peak} (~13.4%) in EXP group & ↓PO_{peak}in CON group (~0.8%)	↑HR_{peak} (~1.1%) in EXP group & ↓in CON group (~4.4%)

(*continued on next page*)

Table 3 (*Continued*)

Study Reference and Quality Score	Study Design	Comparison	Intervention Setting	Exercise Prescription	Standardized Instructions	RPE Familiarization	$\dot{V}O_{2peak}$	$PO_{peak\ and}$ Workload	Other
				Progression: NR				↑PO_{peak}/kg body mass (~27.2%) in EXP group	↑RER_{peak} (~3.9%) in EXP group
Valent et al[30] Level 4 Downs & Black=21	Prospective cohort Study	EXP: ACE CON: none	Home-based and rehabilitation center	Duration: 8 wk Frequency: 2-3 × /wk Intensity: 6-7/10 RPE using CR10 scale (60%-80% HRR) Time: 35-45 min Progression: intensity +1 RPE per 2 wk	NR	NR	Improvement: ↑$\dot{V}O_{2peak}$ (~114%) ↑$\dot{V}O_{2peak}$/kg body mass (~1.8%)	Improvement: ↑ PO_{peak} (~8.3%)	No Change: ↔ Muscle strength ↓Submaximal $\dot{V}O_{2peak}$ (~73%) ↔ Peak RER (~0.01%) ↓Submaximal HR_{peak} (~4%) ↔ Pulmonary function (↑FVC, ↓PEF)
Valent et al[31] Level 2 ROBINS-I=Moderate risk of bias	Prospective cohort study and retrospective age-, sex-, and lesion level—matched control	EXP: ACE CON: 1 or less ACE session per wk	Inpatient rehabilitation centers	Duration: ~17 wk Frequency: 2 × /wk Intensity: 4-7/10 RPE using CR10 scale Time: 40 min. Progression: NR	Yes	NR	Improvement: ↑$\dot{V}O_{2peak}$ in both groups ↑$\dot{V}O_{2peak}$/kg body mass in both groups	Improvement: ↑PO_{peak} in both groups ↑PO_{peak}/kg body mass in both groups	Improvement: ↑Elbow strength in both groups ↑Shoulder strength greater in exercise group ↑Pulmonary function (↑FVC & ↑PEF) in both groups ↑RER in both groups ↔ HRpeak in both groups ↑O_2pulse (mL/beat) in both groups
Van der Scheer et al[37] Level 1 RoB 2.0=Low risk of bias	Randomized controlled trial	EXP: Wheelchair propulsion on a treadmill CON: Non-exercising	Supervised exercise at a rehabilitation center	Duration: 16-18 wk Frequency: 2 × /wk Intensity: 1-3/10 RPE using CR10 scale (30%-40% HRR) Time: 30 min Progression: NR	NR	NR	No change: ↔ $\dot{V}O_{2peak}$ in both groups ↔$\dot{V}O_{2peak}$/kg body mass in both groups	No change: ↔ PO_{peak} in both groups	No change: ↑5-15 m wheelchair push in EXP group & ↔ in CON group ↔ Session-RPE or upper body local perceived discomfort in both groups (fifth exercise session vs last exercise session) ↔Submaximal fitness in both groups ↔ Isometric strength test in both groups ↔ Wheelchair skill performance (performance time & ability score & strain score [%HRR]) in both groups ↔Physical activity levels in both groups (Physical Activity Scale for Individuals with Physical Disabilities [MET·h/wk] & distance [km/wk])

NOTE. Dark gray indicates improvement and light gray indicates no change.

Abbreviations: ACE, arm cycle ergometry; BMI, body mass index; CON, control group; CR10, category ratio 10 scale; EXP, experimental group; FVC, forced vital capacity; HDL-C, high-density lipoprotein cholesterol; HOMA-IR, Homeostasis Model Assessment of Insulin Resistance; HR_{peak}, peak heart rate; HRR, heart rate reserve; MET, metabolic equivalent; MICT, moderate intensity continuous training; NMES, neuromuscular electrical stimulation; NR, not reported; PEF, peak expiratory flow; PO_{peak}, peak power output; RER, respiratory exchange ratio; RoB 2.0, Risk of Bias 2.0 tool; ROBINS-I, Risk of Bias in Nonrandomized Studies of Interventions; RPE, ratings of perceived exertion; SIT, sprint interval training; $\dot{V}O_{2peak}$, peak oxygen uptake. ↑, increase; ↓, decrease; ↔, no change.

measured by $\dot{V}O_{2peak}$ and PO_{peak}, for any adult with SCI was classified as *Low* (see appendix 3.2).

Discussion

This study provides the first summary, appraisal, and meta-analysis of the effects of perceptually regulated exercise training interventions on cardiorespiratory fitness after SCI. The GRADE assessments revealed a *Low* certainty of evidence for significant improvements in $\dot{V}O_{2peak}$ and PO_{peak} after perceptually regulated exercise training and *Low* certainty in the evidence for no difference in $\dot{V}O_{2peak}$ and PO_{peak} when comparing a perceptually regulated exercise training with a control intervention in adults with SCI, using the RPE scale.

There was a wide range of exercise frequency, intensity, time, and modality used in the literature captured in this review. On average, the exercise interventions prescribed included exercise sessions of 38±16 minutes in length, 3±1 times per week for a duration of 10±5 weeks. The calculated mean values for frequency, intensity, and time of exercise intervention used in the 9 studies were similar to the exercise guidelines for adults with SCI.[6] In a cross-sectional study examining the health status of people with SCI, those who were regularly physically active, defined by the exercise guidelines, had improved overall health status.[41] Recent evidence shows high-intensity interval training may be a viable alternative for improvements in cardiorespiratory fitness compared with moderate-intensity continuous training in individuals with SCI.[42] However, a systematic review and meta-analysis that captured 8 pre-post trials, and 8 control trials concluded that high-intensity interval training may be no more effective than moderate-intensity continuous training at improving cardiorespiratory fitness in individuals with SCI.[43] In the current review, low-, moderate-, and high-intensity exercise training interventions were used, yet only 1 control trial prescribed RPE-guided high-intensity interval training in an acute care setting.[35] There is an opportunity to expand on the literature in this area using high-intensity interval training prescribed and monitored by RPE because it provides a time efficient and practical alternative for exercise training in individuals with SCI.

When comparing RPE-guided exercise with control, there was no difference in $\dot{V}O_{2peak}$ and PO_{peak} in adults with SCI. In the current study, there was a large SD in the frequency, intensity, time, and type of exercise training across the 3 eligible studies included in this secondary analysis. While the number of studies eligible to answer this question is low, there are limitations to using RPE to guide exercise intensity. The heterogeneity of the population of individuals with SCI, variability in the RPE response between individuals, and lack of reporting on the familiarity of participants and researchers are 3 challenges captured in this review. In the studies that reported prescription language, there were 3 categories of exercise intensity: light/low, moderate, and hard/vigorous/sprint. Eight of 9 studies used a range of RPE prescription that spanned 3 RPE points, which fell within more than 1 intensity category. For example, an RPE of 3 of 10 could fall within both the light and moderate category when comparing across studies. There is variability in an individual's response to RPE, which was previously shown in a systematic review concluding that RPE has low criterion validity in individuals with SCI.[5] While RPE as a prescription method is practical, the variability in exercise responses could lead to an individual exercising above or below their lactate threshold, as previously discussed,[44] which may ultimately enhance or hinder an improvement in cardiorespiratory fitness. In this review, 4 studies recruited participants with a history of exercise training and/or indicated some level of supervision during exercise training. When individuals are untrained, lack familiarity with RPE, or complete exercise in an unsupervised setting, there is typically an increase the variability in RPE response.[5]

The GRADE assessments of *Low* certainty of evidence were aligned with the limited amount of literature and heterogeneity in both the population and training interventions as discussed above. For an increase to a level of *High* certainty of evidence, higher-quality studies (i.e., more randomized controlled trials) or interventions with a higher training load that lead to a larger change in cardiorespiratory fitness or PO_{peak} (i.e., greater effect size) must be conducted to eliminate any *imprecision* identified by the GRADE scoring criteria.[27] Training volume (i.e., training load) is the product of training time and intensity and is typically calculated on a weekly basis.[45] Alternative to an increase in training intensity, as we suggested earlier in the discussion, an increase in training frequency or training duration can lead to an overall increase in the training time and therefore training volume. While it is outside the scope of this review, the decision on how to increase training load should be codeveloped using individualized goals that may lead to increased exercise adherence.[46]

There is a body of literature to suggest self-selected exercise intensity leads to greater exercise enjoyment and affect in individuals with SCI,[47] which may improve self-efficacy and may positively affect exercise and physical activity behavior.[48-50] In the current study, there was an average of 86%±11% adherence to the exercise training sessions prescribed. This level of adherence is high considering that individuals with SCI are among the lowest on the physical activity spectrum[51] and experience many psychological and physical barriers to physical activity participation.[7] Additional research examining long-term unsupervised perceptually regulated exercise training interventions is needed to enhance our understanding.

Previous systematic reviews suggest there is evidence to indicate exercise-related adverse events are rare for individuals with SCI when appropriate safety precautions and exercise guidelines are followed.[6,52] In the 9 studies captured by this review, no training was stopped because of complaints; however, there was 1 adverse event that occurred post exercise after sprint interval training and 3 occasions in which participants needed to postpone the next training session or to reduce the exercise intensity. These findings align with the work of Warms et al., who also noted no serious adverse events associated with cardiovascular-related training programs.[52]

Study limitations

This review and analysis of the literature is not without limitations. Given the complexity of traumatic SCI and a small participant pool, our study population is reflective of a typical underrepresentation of women and older individuals. In addition, there is a high level of heterogeneity in the population of individuals with SCI that depends on the neurologic level, completeness of injury, and time since injury. A complete injury at a high lesion level, specifically above the sixth thoracic vertebra, will likely have a greater effect on cardiovascular function which will likely affect both the acute exercise response and the chronic exercise training adaptations compared with an individual with an incomplete and/or lower-level injury.[10] The low number and type of studies captured in this review may limit the generalizability of these findings.

Implications for future research

One of the promising aspects of this review is the growing interest in the exploration of exercise prescription in populations with SCI. This review captured a wide range of duration of exercise training studies with the longest duration of 18 weeks. As identified in this review, perceptually regulated exercise training has cardiorespiratory fitness and PO_{peak} benefits for individuals with SCI; however, it is not yet understood if this research translates to lower risk of cardiovascular disease, reductions in the occurrence of secondary health conditions, and improvement in subjective well-being similar to previous benefits that have been shown with traditionally prescribed exercise interventions in adults with SCI.[53-55] The literature is lacking in high-quality studies that compare different types of exercise prescription methods and long-term adherence. While long duration randomized controlled trials are challenging to implement, an opportunity exists to conduct research in a home-based or community setting. There were 2 studies that took place in a home-based setting[29,30] and 1 study that occurred in a community exercise facility,[28,33] all of which found participants improved $\dot{V}O_{2peak}$ and PO_{peak} after perceptually regulated exercise interventions.

Perceptually regulated exercise training has practical and theoretical advantages for both healthy and clinical populations; however, RPE is the most widely researched of the subjective scales used to gauge exercise intensity. Since the development of the RPE, the subjective exercise intensity scale has been used to prescribe aerobic and resistance exercise training interventions in athletes, elderly persons, and clinical populations.[11,56,57] Recent research has revealed the interchangeability of Borg's 6-20 scale and the CR10 scale for exercise prescription in healthy individuals and those with SCI.[44] While we included all types of perceptual scales for exercise prescription, exercise prescription of the studies captured in this review used either the 6-20 RPE scale (n=2) or the CR10 scale (n=7), which have been shown to have some validity and good reliability in individuals with SCI.[5] Standardized instructions and familiarization using the RPE scale are 2 important steps to ensuring reliability of the scale, especially given the heterogeneity of the population with SCI and the wide range of exercise prescriptions (ie, duration, intensity, modes, etc) used in exercise interventions. Based on the inclusion and exclusion criteria, all participants recruited for the included studies may have been prescribed medications that alter their heart rate; however, participants in 6 of 9 studies were likely on stable medical therapy. An advantage of RPE is the level of association with exercise intensity, despite the use of heart rate−reducing medications in patients with coronary artery disease completing exercise cardiac rehabilitation[58]; however, this relationship has not been investigated in individuals with SCI. Of the 9 studies in the current study, only 1 journal article described the RPE standardization instructions used, and 3 studies described the process of RPE familiarization in their study design. Future research that incorporates the use of RPE to prescribe and monitor exercise intensity for individuals with SCI should incorporate and report on whether there are standardized instructions and familiarization using the RPE scale.

Conclusions

The implementation of perceptually regulated training improves cardiorespiratory fitness and PO_{peak} as a prescription and monitoring method for SCI exercise training interventions. Subjective measures, specifically RPE, can be used to prescribe exercise; however, RPE familiarization and standardized instructions are 2 key steps when verifying intensity within research. Given the practical advantages of RPE, future research may aim to incorporate RPE into home-based and high-intensity exercise prescription for individuals with SCI. This research will inform future perceptually regulated exercise interventions in individuals with SCI.

Suppliers

a. Covidence systematic review software; Veritas Health Innovation. b. WebPlotDigitizer Version 4.4; Ankit Rohatgi. c. RevMan v5.4; Cochrane Collaboration.

Keywords

Exercise; Paraplegia; Quadriplegia; Rehabilitation

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Chapter 3: Leg muscle strength and power predict rating of perceived effort during cardiopulmonary exercise testing.

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3.1 Abstract

Background: The effort required to cycle progressively intensifies during incremental exercise to peak capacity. The determinants of the perceptions of leg cycling effort have not been assessed in large samples where sufficient response variation permits definitive characterization of relationships. **Methods:** The perceived intensities of the effort required to cycle was rated during incremental exercise to symptom-limited capacity by 35,597 participants (53±17yrs, 60% male) referred from 1988 to 2012 by matching the perceived intensities to quantitative semantic terms tagged to numbers from 0-10 (modified Borg scale). Prior to cardiopulmonary exercise testing, height, weight, age, muscle strength, pulmonary function, hemoglobin, and arterialized capillary blood gases were measured. **Results:** The perceived effort required to cycle was determined by cycling power (power) and the maximum cycling power output (P_{MAX}): perceived leg cycling effort = power $^{2.12}$ ● $P_{MAX}{}^{-1.86}$ (r=0.8159). Forward stepwise linear regression revealed that there was additional predictive capacity with the addition of quadriceps strength to the perceived leg cycling effort equation. The additional Inclusion of height, age and sex to the relationships contributed minimally. **Conclusion:** During incremental cycling exercise, perceived leg cycling effort intensifies with increasing power and inversely with the peak capacity to exercise (P_{MAX}). The P_{MAX} achieved was dependent on leg strength. This study suggests that leg cycling exercise tolerance is limited, in part, by the perceptual consequences of exercise that are primarily dependent on leg strength.

3.2 Introduction

Cardiopulmonary exercise tests (CPETs) are used in the management of heart, lung, and musculoskeletal disorders. The peak exercise capacity is used in the assessment of disease and condition identification, progression, and treatment and in risk stratification. Previous research suggests that peak exercise capacity is constrained by oxygen delivery and carbon dioxide removal by the heart and lungs (Lundby et al., 2017). Exercise tolerance requires an individual to tolerate the perceptions associated with exertional effort (Tenenbaum, 2001). In practice, exercise intolerance is defined as the inability to perform or sustain physical exercise to normal expected standards (Palange et al., 2006). The combination of physiological and psychological limits during exercise are unique to each individual.

During cycling exercise, sensations, and their perceptual interpretation, arise in relationship to the muscles required to cycle (leg muscles) and breathe (respiratory muscles) because both share the same sensory properties. Primary afferents communicate ascending signals to the thalamus and thereafter to the primary sensory cortex and signals transmitted by specific nerves give rise to both the five special senses and other body sensations, including pain, temperature changes, itching, and pressure (Müeller, 1835). Mueller also recognized that the perceived sense of muscular effort arose in relationship to the intensity of the central outgoing motor command from the primary motor cortex (Müeller, 1835). When exercising, afferent pathways contribute to the responsiveness of the alpha motor unit driving the peripheral muscles and influence the outgoing central command required to generate power (Taylor et al., 2016). In the late eighteen hundreds, Ferdinand LaGrange addressed the thermodynamics of exercise, recognizing that the exercise performed was limited by fatigue and breathlessness to which he devoted several chapters (Lagrange, 1898). Currently, fatigue is defined by an increase in the central motor drive required to sustain the same power over time and, as such, is intimately associated with the perception of effort (Enoka & Duchateau, 2008).

During a CPET, perceived exertion increases in concert with the power required to cycle and breathe until the point at which an individual is unable to tolerate the sensations. Perceived exertion can be quantified by matching the perceived effort to quantitative sematic terms associated with numbers from 0 to 10 using the modified Borg scale (Borg, 1982). Assessing the perceived leg cycling and breathing efforts during an incremental exercise test to peak capacity across the spectrum of health and disease provides a unique opportunity to understand the physiological contributors in a manner not previously addressed. Previous research suggested that muscle activation measured by electromyography and ventilatory work measured by respiration rate are the strongest factors influencing “the sense of effort” ratings of perceived exertion. Previous work published by Satia and colleagues focused on the factors related to breathing effort (Satia et al., 2020), however similar examinations of the effort to cycle have not been conducted (Cafarelli, 1977, 1982; Chen et al., 2002). Height, weight, age, and sex are commonly used to derive reference standards for CPETs in a sample of the “normal” population and the perceived exertion required to cycle and breathe are simply used to confirm peak exercise capacity was reached (Jones et al., 1985). However, previous research focussed mainly on the relationships between heart rate and ratings of perceived exertion and neglected to acknowledge the role of maximum cycling power output (P_{MAX}) and muscle strength as potential mediators of the relationship between perceived exertion and exercise tolerance. Subtle changes in quadriceps muscle strength are related to the independence of an individual throughout their daily activities (Schoser et al., 2017; Wearing et al., 2019). For example, the reduction in quadriceps strength for an elderly individual may lead to a reduced capacity to stand up from a chair, therefore losing their independence to move from sitting to standing. P_{MAX} has been previously identified to be dependent on exercising muscle strength, ventilatory and circulatory factors relative to metabolic demand (Hamilton et al., 1995).

In this study the relationships between physiological variables and perceived leg cycling effort measured throughout an incremental exercise test to capacity were explored in a large retrospective data set. The objective was to determine the predictors of perceived intensity of the effort required to cycle during an incremental cycle ergometry test to capacity to better inform the use of ratings of perceived intensity in the future.

New and Noteworthy

1. Assessing ratings of perceived exertion, in a large sample, across a wide range of health conditions and exercise capacities offers a unique opportunity to examine the relationships between physiological constraints and perceived exertion during exercise.
2. During cardiopulmonary exercise testing, the perceived intensity of the effort required to cycle increased in a positively accelerating manner as cycling power increased (kpm/min) and as maximum cycling power output decreased. The rate

of acceleration in perceived leg cycling effort increased as maximum cycling power output decreased.

3. The ability to perform leg cycling exercise is mainly dependent on maximal exercise power output, and therefore on leg muscle strength. Our findings suggest in the future, interventions should focus on increasing exercising muscle strength to address exercise intolerance.

3.3 Methods

Study design and participants

This was a retrospective study conducted using data collected from participants who completed a CPET at McMaster University Medical Centre from 1998 to 2012. This study was approved by the Hamilton Integrated Research Ethics Board (#14655). Written and signed informed consent for exercise testing was obtained at time of data collection after the risks were explained. The study included 35,597 participants referred for CPET, including patients with cardiovascular and congenital heart disease, patients with obstructive and nonobstructive pulmonary disease, patients screened prior to rehabilitation programs in the elderly and normal participants. Patients were excluded if they did not complete a minimum of 3 stages (up to 300 kpm) or completed greater than 16 stages (1700 kpm or greater) of the CPET, thereby excluding the extremes of both low and high-power outputs. The dataset includes ~17,000 participants that completed the CPET, however they have no medical chart reported medical condition.

Study procedures

Prior to each CPET, pulmonary function testing was completed and muscle strength was measured using maximum voluntary contractions performed against a viscoresistive hydraulic device (Hamilton et al., 1996) during seated bench press and row, and knee extension (quadriceps). A full description of the assessments conducted has been previously published (Satia et al., 2020). Graded exercise testing was conducted on a servo-controlled cycle ergometer using guidelines for stage 1 exercise testing introduced by Jones (Jones, 1997). The workloads were independent of cycling frequency from 45 to 95 rpm. The power output increased by 100 kpm (16 Watts) each minute, until symptom limited capacity. At each workload, the leg cycling effort was measured by matching participant reported perceived exertion intensity to quantitative semantic terms tagged to numbers from 0-10 (the modified Borg scale) (Borg, 1982). Study participants wore a mouthpiece and a nose clip throughout exercise and oxygen uptake, carbon dioxide output, respiratory exchange ratio (RQ), end tidal oxygen (O_2), carbon dioxide (CO_2), mixed expired O_2 and CO_2, ventilation, tidal volume, respiratory frequency, blood pressure, and heart rate were monitored. The physiological data were averaged over the time spent at each workload. P_{MAX} was defined as the P_{MAX} achieved and sustained for at least 30s during the CPET. Electrocardiogram monitoring was conducted continuously from rest until 10 minutes post exercise.

Statistical analysis

Means, standard deviations, medians, upper and lower quartiles, percentiles, and ranges were calculated for the potential predictors to the perceived leg cycling effort and to P_{MAX}. Forward stepwise additive linear regressions were used to identify the contribution of height, weight, age<20, age>35, sex, quadriceps strength, forced expired volume over 1-second (FEV_1) and diffusing capacity of the lungs of carbon monoxide (DLCO), power to the perceived efforts required to cycle. We examined the relationship between quadriceps strength and age to determine the approximate inflection points that occur at the end of maturity and the beginning of age-related decline. Age was included as a dichotomous variable as muscle mass increases with increasing age up to 20 years of age (maturation) (Armstrong & Welsman, 1994) and subsequently decreases with increasing age after 35 (20). We conducted additive stepwise linear regression to identify the factors contributing to the capacity to generate P_{MAX} for perceived leg cycling effort. We then conducted further analysis to assess potential determinants of P_{MAX} with the following variables: height, weight, age<20, age>35, sex, quadriceps strength, FEV_1 and DLCO.

Entry and removal criteria for the additive stepwise linear regression were set to p=.01 and p=.02, respectively. The alpha criterion for the model was set to .01. The contribution of cycling power at each stage of the CPET and the P_{MAX} were explored as independent contributors to the perceptions of the intensity of the effort required to cycle during incremental exercise to capacity using multiple analysis of variance (MANOVA). The interaction of power and P_{MAX} was also explored using nonlinear interactive regression analysis to generate equations to quantify their contribution. All statistical analyses were conducted on statistical software (Statistica version 13.2, StatSoft; Germany).

3.4 Results

The available data set included data from 42,791 individuals who completed a CPET during which P_{MAX} achieved ranged from 0-2400 kpm/min. The study population for the current study was confined to those achieving a P_{MAX} ranging from 300 to 1600 kpm/min leaving data from 35,597 individuals available for analysis. Restricting the P_{MAX} as an inclusion criterion eliminated potential outliers including those who failed to perform any exercise for unclear reasons and individuals achieving greater than 1600kpm/min given that we could not account for the potential of extreme variations in training status. Participant demographics, baseline, and CPET characteristics are shown in Table 1.

The perceived intensity of the effort required to cycle increased in a positively accelerating manner as power increased (kpm/min) and as P_{MAX} decreased (Figure 1). The rate of acceleration in perceived leg cycling effort increased, as P_{MAX} decreased as shown in Figure 1. Power at an individual stage of the CPET and P_{MAX} were the dominant contributors to the perceived intensity of the effort required to cycle. The predictive interactive non-linear equations describing these results are: Perceived Leg Cycling Effort = $\text{Power}^{2.12} * P_{MAX}^{-1.86}$, r=0.8159.

Potential independent contributors to the observed variance in P_{MAX} were considered in a forward stepwise linear model that included height, weight, age<20, age>35, sex, quadriceps strength, FEV_1, and DLCO. Height, weight, age<20, age>35, sex, contributed minimally to P_{MAX} with the prior addition of quadriceps strength, FEV_1 and DLCO (Table 2). We used additive stepwise linear regression to determine the single strongest contributing independent variables to P_{MAX}. The variables considered to replace P_{MAX} were quadriceps strength, FEV_1, DLCO, age<20, age>35, sex, weight, and height. The predictive non-linear equations can be described as follows: [Perceived Leg Cycling Effort = 1.072 + 0.005Power – 0.028Quadriceps Strength, r=0.72, β=0.76 (Standard error of β = -0.23)]

Examination of the relationship between $\dot{V}O_2$ and power for this data set was conducted and is represented by the following equation: $\dot{V}O_2$(ml/min) = 332 + 1.7Power (kpm/min); r =0.95, SEE=200. In 51.82% of participants the perceived leg cycling effort exceeded the perceived effort required to breathe at P_{MAX}, while in 13.09% the reverse was true and in 33.93% the effort required to breathe, and leg cycle were rated as equal at P_{MAX} (i.e., leg cycling effort and breathing effort both rated as 7 out of 10). Any participant that mentioned chest pain, even in combination with other symptoms, were categorized as limited by chest pain. The proportion of participants limited by chest pain alone, or in combination with other symptoms, was 1.15%.

N = 35,597 (male 60%)	Mean	Standard deviation	Lower Quartile	Upper Quartile	5th %ile	95th %ile	Range (min.)	Range (max.)
Age (yrs)	53	17	44	66	16	76	6	95
Height (m)	1.69	0.10	1.62	1.76	1.52	1.84	1.18	2.07
Weight (kg)	78.5	18.5	66.1	89.0	51.0	110.0	20.0	206.0
BMI (kg/m^2)	27.4	5.4	23.9	30.1	19.5	36.9	11.1	68.9
Quadriceps Strength (kg)	46	19	31	59	17	81	3	143
Bench Press Strength (kg)	56	24	37	74	21	100	2	158
Upright Row Strength (kg)	44	18	31	56	19	76	1	172
Resting MIP (cmH$_2$O)	75	30	51	96	30	128	3	239
Resting MEP (cmH$_2$O)	106	37	80	130	50	172	1	300
Resting DLCO (ml/mmHg/min)	22.53	6.55	17.80	26.90	12.50	33.90	2.60	54.40
Resting KCO (ml/mmHg/min/L)	4.41	0.99	3.77	5.00	2.87	6.09	0.34	11.60
Resting $\dot{V}A$ (L)	5.19	1.31	4.20	6.10	3.10	7.30	0.80	10.70
Resting FEV$_1$ (L)	2.75	0.85	2.10	3.30	1.40	4.20	0.30	6.70
Resting VC (L)	3.45	1.00	2.70	4.10	1.90	5.20	0.70	8.30
Resting PEFR (L/sec)	6.99	2.22	5.40	8.50	3.60	10.80	0.80	17.60

Resting PIFR (L/sec)	4.99	4.18	3.70	6.10	2.40	8.00	0.00	715.00
Resting BP, systolic (mmHg)	130	21	110	140	100	170	60	250
Resting BP, diastolic (mmHg)	76	10	70	80	60	90	40	120
Resting HR (bpm)	78	15	67	88	55	104	37	168
Resting $\dot{V}$E (L/min)	12.80	3.64	10.40	14.60	8.00	19.20	2.10	70.90
Resting PETCO$_2$ (mmHg)	34.26	3.67	32.10	36.70	27.80	39.80	16.10	58.70
Resting PECO$_2$ (mmHg)	20.16	4.49	17.51	23.23	11.83	27.01	3.32	36.99
Resting Hb (g/dL)	13.79	1.47	12.80	14.80	11.40	16.10	5.10	21.60
$\dot{V}$O$_2$peak (L/min)	1.62	0.65	1.13	2.02	0.74	2.85	0.12	4.70
$\dot{V}$CO$_2$peak (L/min)	1.76	0.74	1.20	2.23	0.73	3.15	0.09	5.13
HRpeak (bpm)	140	29	119	162	140	141	40	248
P$_{MAX}$ (kpm/min)	790	302	600	1000	400	1400	300	1600

Table 1. BP = blood pressure, BMI = body mass index, DLCO = diffusing capacity for carbon dioxide, FEV1 = forced expired volume over 1 s, KCO = carbon monoxide transfer coefficient, Hb = hemoglobin, HRpeak = heart rate peak, max = maximum, min = minimum, MIP = maximal inspiratory pressure, MEP = maximal expiratory pressure, P$_{MAX}$ = maximum power, PEFR = peak expiratory flow rate, PECO$_2$ = partial pressure of expired carbon dioxide, PETCO$_2$ = end-tidal carbon

dioxide, PIFR = peak inspiratory flow rate, $\dot{V}A$ = alveolar volume, VC = vital capacity, $\dot{V}E$ = minute ventilation, $\dot{V}O_2$peak = peak oxygen uptake, $\dot{V}CO_2$peak = peak expired carbon dioxide. All variables were measured at rest unless otherwise noted.

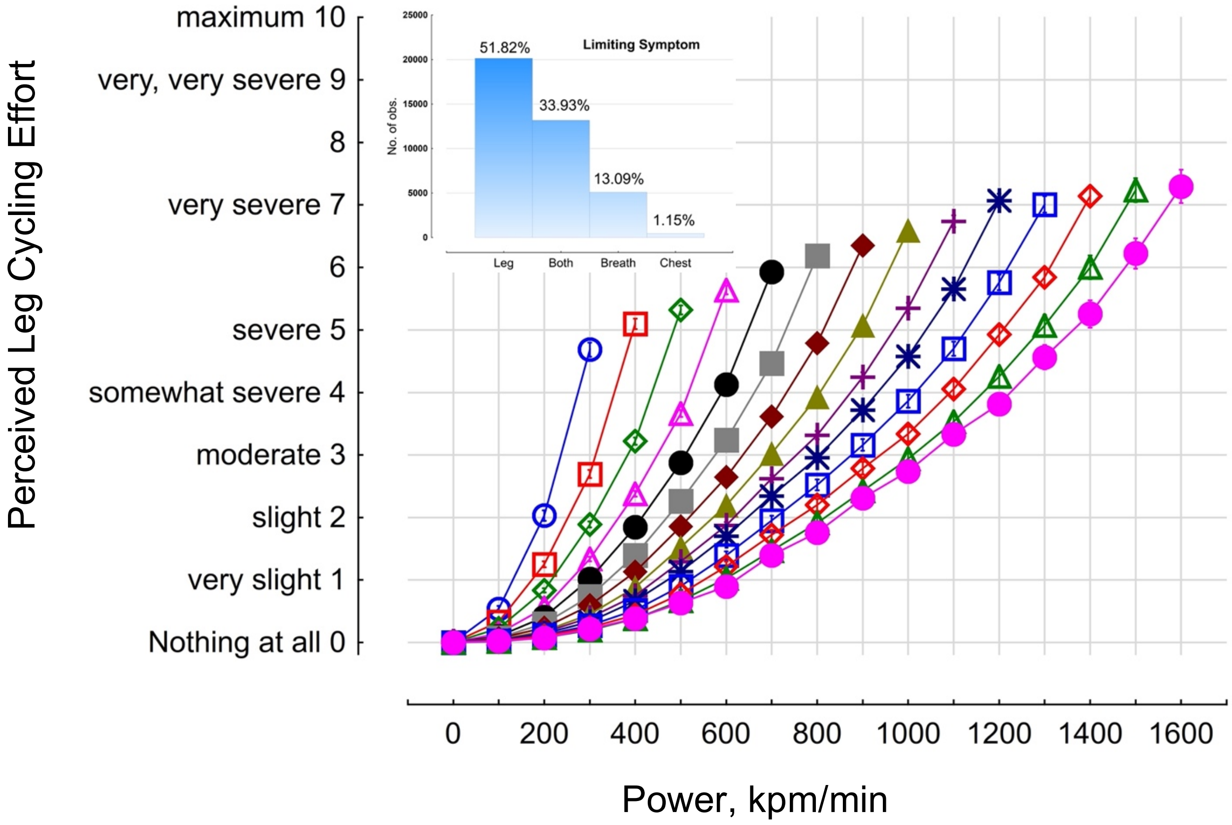


Figure 1. Perceived leg cycling effort during a CPET starting at 0 kpm/min (up to 1600 kpm/min) in 35,597 participants. The symbols and colours represent the grouped data based on their P_{MAX}. The inset graph describes the percentage of

individuals that experienced perceived leg cycling effort as the limiting symptom for exercise. The various colours and shapes represent the individual responses have been averaged into groups based on the P_{MAX} they achieved corresponding with the rightmost value on the x-axis (e.g., open blue circles represent the group with a P_{MAX} of 300 kpm/min). The equation that describes the graph is as follows: Perceived Leg Cycling Effort = $\text{Power}^{2.12} * P_{MAX}^{-1.86}$, r=0.8159.

Table 2. Regression summary table. DLCO = diffusing capacity for carbon dioxide, FEV_1 = forced expired volume over 1s.

	Summary of stepwise regression: Dependent variable = P_{MAX}					
Variable	R	R^2	R^2 Change	F	P-value	Variables included
Quadriceps Strength	0.7243	0.5246	0.5246	36905.03	0.0000	1
FEV_1	0.7935	0.6296	0.1050	9481.96	0.0000	2
DLCO	0.8072	0.6515	0.0220	2108.37	0.0000	3
Age<20	0.8141	0.6627	0.0112	1112.19	0.0000	4
Age>35	0.8160	0.6645	0.0018	175.56	0.0000	5
Sex	0.8164	0.6659	0.0014	141.83	0.0000	6
Height	0.8167	0.6665	0.0005	53.51	0.0000	7
Weight	0.8169	0.6674	0.0009	92.19	0.0000	8

3.5 Discussion

The perceived leg cycling effort intensified in a positively accelerating manner with increases in power in 35,597 participants undergoing a CPET. At any given power the effort required to cycle increased as the P_{MAX} decreased. The power generated by the leg muscles represents a large portion of the variability associated with perceived exertion required to cycle. The workload setting on the cycle ergometer determined the required leg power at each stage whereas as the power generated by the respiratory muscles was determined by the ventilation requirements at each stage with a resistance and elastance varying across participants. Exercise termination was impacted by the subjective experience of the power required to cycle (perceived leg cycling effort) and breathe (perceived breathing effort), which was, in turn, determined by the factors influencing P_{MAX} particularly quadriceps strength as a determining factor for leg cycling effort.

During the incremental and progressive CPET examined in this study the power generated by the legs increased by 100 kpm/min each stage to the P_{MAX}. The P_{MAX} generated by individual participants increased with increasing quadriceps strength, FEV_1, and DLCO (Table 2). Surprisingly, the further addition of age, height and sex contributed only modestly to the predictive capacity of the equation for $P_{MAX.}$ Age, height, and sex appeared to influence the capacity to cycle through differences in the physiological variables of muscle strength, FEV_1 and DLCO. During exercise, the perceived efforts required to cycle and breathe both increased in a positively accelerating manner, whereby either perceived leg cycling effort or perceived breathing effort, were cited as the perceived limiting factors in 98.85% of the CPETs. In 51.82%

the leg cycling effort was cited as limiting, in 13.09% the effort required to breathe was identified as limiting and in 33.93% both were rated as equally limiting. The tolerance threshold was typically not at the maximum of the scale with the average participant ceasing exercise when the effort was perceived as “very severe” (Borg 7). Study participants also varied in their maximum ratings for the effort required to both cycle and breathe a low of “somewhat severe” (Borg 4) to a high of “maximal” (Borg 10).

While previous research was conducted to determine reference standards for CPETs based on height, age, weight, and sex, there exists a gap in identification of relationships to other physiological traits (Jones et al., 1985). Specifically, previous reference standards do not include considerations of quadriceps strength and P_{MAX}, which we found were the strongest mediators for peak exercise capacity. Our results now provide a reference for a broad group of individuals presenting identifying factors that contribute to exercise performance and tolerance across health and disease. Another retrospective study, including 9551 tests conducted on both a treadmill (n=8821) and a cycle ergometer (n=730) in 13 laboratories, excluded individuals with cardiovascular disease and chronic obstructive pulmonary disorder and found that 83% of individuals reached a perception of effort of 18 or greater out of 20 in a CPET (Peterman et al., 2023). The current study supports the concept that exercise is perceptually limited by the tolerance for the effort required to cycle that has historically been connected to fatigue and pain. Fatigue has been long linked to the perceptual factors limiting muscular exercise where fatigue is defined by the increasing motor command and perceived effort required to sustain the same power over time (Lagrange, 1898). However, recent research corroborates these findings that individuals can consciously separate the sensations of pain and effort during exercise (Hamilton et al., 1995; Marcora, 2009).

Physiological Constraints to the Capacity to Exercise: Perceived Leg Cycling Effort

There is a long-held belief that oxygen delivery is “the” physiological limiting factor to the capacity to whole body exercise (Hawley et al., 2014). Oxygen is consumed in the generation of power making it important to discriminate whether it is the power or the oxygen uptake that is limiting. Increases in power cannot be sustained without corresponding increases in oxygen consumption ($\dot{V}O_2$peak) (Richardson et al., 1995). In the current study the relationship between $\dot{V}O_2$peak and power was so close that these variables could be used interchangeably in this population as represented by the following equation: $\dot{V}O_2$(ml/min) = 332 + 1.7Power (kpm/min); r =0.95, SEE=200. In essence, $\dot{V}O_2$peak is the metabolic cost of the generation of P_{MAX}.

Typically, maximal strength is measured by asking the individual to generate maximal motor effort and measuring the force generated. Variability in generating the maximum motor command has been previously examined using the interpolated twitch technique, whereby motor unit activation indices in the low 90% are usually found (Gandevia et al., 1995). Muscle mass and strength vary widely and the contribution of this variability to the maximal capacity to generate power during exercise (P_{MAX}) is worthy of concern when conducting CPETs in individuals with exercise intolerance. While all muscle groups have a high degree of variability in maximum strength, all muscles weaken and have greater fatigue with continued high intensity exercise (Wan et al., 2017). The rate of fatigue declines as force generation decreases from maximum but the rate of fatigue at any given submaximal power varies for a variety of contributing muscle groups (Wan et al., 2017). Taken together, we suggest the use of maximal strength testing can be used as an alternative and/or adjunct to CPET. Future research may lead to the development of a muscle specific strength test to predict maximal power on the leg cycle ergometer when completion of a CPET is not feasible.

Average ratings of perceived exertion at the end of a CPET

Exercise limitation during incremental activity to capacity using large muscle groups should rationally include the perceived intensity of efforts of the exercising and respiratory muscles (Sheel et al., 2018). Limb and respiratory muscles are both striated skeletal muscles with similar sensory properties. Based on these results, the effort required to cycle are forwarded in the current study as perceptual limitations where the discomfort associated with leg cycling are predominantly a function of the sense of effort required to activate these muscle groups. The mean limiting intensity for perceived leg cycling effort was 7, corresponding to “very severe” and varied from “somewhat severe” to “maximum”. While individuals often exercise to their perceptual tolerance, tolerance varies. In psychophysical terminology this variation is referred to as response bias which will vary within, and across, individuals depending on the individual circumstances and differences in life experience and attitude (Dodd-McCue & Tartaglia, 2010). In the current study only 1.15% of participants were limited by exertional chest pain and this agrees with previous literature where adverse events associated with graded exercise testing occur at a rate of 0.8-1.2 per 10,000 tests (Dun et al., 2021; Myers et al., 2000).

The criteria limiting exercise are usually based on measurements made under maximum exercise conditions. Typically, the limiting factor has been identified as related to the required energy to complete maximal exercise (Hargreaves & Spriet, 2020) or to cardiovascular and pulmonary limitations often attributed to oxygen transport (Bassett & Howley, 2000). Here we propose that while energy consumed at peak exercise is a function of the power generated, volitional exhaustion is dependent on the perceived effort required to cycle and is a key component of graded exercise testing. The physiological contributors to perceived exertion, including muscle strength and power, are important determinants of exercise tolerance in health and disease. Previous guidelines statements have not included the measurement of muscle strength as part of routine CPET and this has perpetuated an underestimation of the utility of muscle strength testing in used combination with CPET ("ATS/ACCP Statement on Cardiopulmonary Exercise Testing," 2003; Glaab & Taube, 2022). Our results indicate that baseline muscle strength and power assessments may provide additional predictive power and a further basis for a focus on muscle strength in subsequent exercise prescription.

This study supports strength testing as a feasible alternative and adjunct to CPET assessment. Functional strength and power assessments, such as the timed up and go test and handgrip strength assessment, have been used in outpatient and community exercise settings for determination of risk based on normative values and percentiles (Beauchamp et al., 2022; Mayhew et al., 2023). Regardless, there are inherent strengths to CPET for determining health status that may not be addressed by strength testing alone (Suzuki et al., 2004).

3.6 Strengths and limitations

Our study includes data from a large cohort of individuals representing a spectrum of health and disease conditions, each of whom completed comprehensive assessments of physiological function, including a CPET, and assessments of muscle strength. Limitations include the fact that the cross-sectional data were collected only at one location, and it is unclear whether the results would be different if the participants were tested over time and in different assessment locations. While underlying comorbidities were not described in detail, the individuals in this study did not have any underlying sensory system dysfunction that would have altered the perceptual assessments. Maximal dynamic voluntary contractions on a hydraulic resistance device to measure peak quadriceps force are not a routinely available method for the measurement of muscle strength. However, the strength measured in one muscle group (quadriceps via leg extension) was indicative of the muscle strength in other muscle groups (see Supplemental File 1), and these results may be translated to commonly available methods for assessment of muscle strength, such as grip strength.

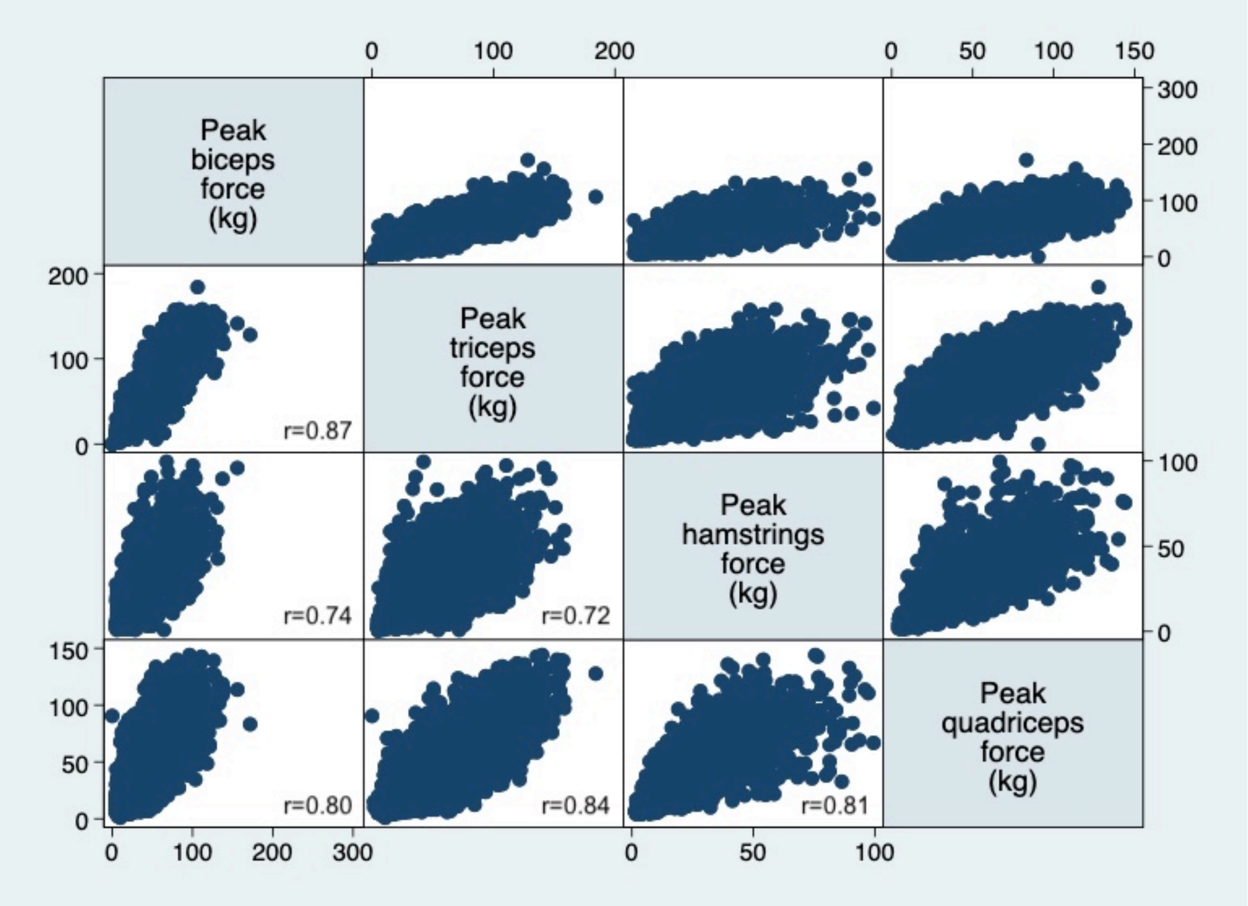
Building on previous work on the effort required to breathe (Satia et al., 2020), we conducted the effort required to leg cycle. It is unlikely that these symptoms of exercise intolerance are isolated or independent.

3.7 Conclusion

Quadriceps strength and power were the strongest predictors of perceived effort required to cycle during a CPET. This study suggests that the perception of exercise limits exercise tolerance, which is, in turn, influenced by muscle strength and power.

Based on these results, we recommend that muscle strength and power should be routinely assessed in patients completing CPET.

Supplemental File 1. Each graph matrix represents the scatterplot between the variables in the corresponding row and column. The r-value represents the correlation between the corresponding column and row variables. For example, the scatterplot below the cell that is labelled peak biceps force, describes the relationship between peak biceps force and peak triceps force. There is a positive strong relationship between all muscle strength variables.



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Chapter 4: Exploring both individual and healthcare professional perspectives of using ratings of perceived exertion for exercise during rehabilitation after a spinal cord injury.

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4.1 Abstract

Background: The Canadian physical activity guidelines for individuals with a spinal cord injury (SCI) recommend 20-30 minutes of moderate to vigorous activity two to three times per week. Individuals with an SCI experience different physiological sensations during exercise which may include altered sweat response, blunted heart rate, and altered ability to activate muscle groups impacting their ability to gauge exercise intensity. Ratings of perceived exertion (RPE) are commonly used to prescribe exercise intensity in rehabilitation settings; however, little is known about what sensations individuals with paraplegia (PP) and tetraplegia (TP) use to gauge their intensity outside of the clinic or laboratory. **Objective:** This research aimed to examine the perceptions of exercise intensity from the perspective of individuals with SCI, and healthcare practitioners who work with individuals with a SCI in a rehabilitation setting. **Methods:** Semi-structured interviews were conducted with 15 individuals with SCI (11M/4F; 6PP/9TP) and 5 healthcare professionals (0M/5F) recruited from community gyms and hospital settings. A follow-up interview was conducted on a separate cohort of 18 individuals with SCI (15M/3F; 10PP/8TP) after completion of both moderate and high intensity arm cycling exercise. The interview transcripts were team coded using an inductive analysis approach. **Results:** Muscle tension was the most common sensation that was used to gauge exercise intensity, followed by fatigue, and breathing. Additional analysis of reflections after arm cycling, indicated that while there was considerable variety in how participants described their individualized RPE scales, language related to muscle sensations would likely assist with use of RPE during exercise. **Conclusions:**

This research may be used to inform the use of RPE to prescribe and monitor exercise intensity in individuals with SCI.

4.2 Introduction

The Canadian physical activity guidelines for individuals with a spinal cord injury (SCI) recommend 20-30 minutes of moderate to vigorous intensity aerobic physical activity two to three times per week (Martin Ginis et al., 2018). Muscle strengthening activities are prescribed as 3 sets and 10 reps, two times per week, however there is no intensity prescription. It has been suggested that these guidelines may lead to cardiometabolic benefits and ultimately stave off the risk of inactivity-related diseases (Martin Ginis et al., 2018). The lifespan of individuals with SCI has increased with advances in healthcare, however the highest mortality risk in this population remains cardiovascular disease (Barton et al., 2021). Only exercise training and sports have been shown to improve cardiovascular health and wellbeing in individuals with SCI (Jörgensen et al., 2019; van der Scheer et al., 2017). Therefore, it is a responsibility of policy makers and researchers to provide accessible methods for achieving the health benefits conferred by adhering to the exercise guidelines. Recently, researchers have raised concerns about intensity prescription for individuals with SCI (Hutchinson & Goosey-Tolfrey, 2021; Nightingale et al., 2018) given that intensity is one of the most challenging elements of exercise prescription for health benefits in all populations (MacInnis & Gibala, 2017; Coates et al., 2023). In addition, evidence is building for high intensity interval training as a time-efficient alternative for individuals with SCI (Astorino et al., 2021; Peters et al., 2021), yet how to gauge intensity is an essential, yet relatively understudied, element of exercise prescription in high intensity interval training. One solution that has been proposed is replacing the vague language around “moderate and vigorous intensity” and instead use ratings of perceived exertion (RPE), a subjective method of evaluating exercise intensity (Borg, 1962; Hutchinson & Goosey-Tolfrey, 2021). RPE is already a popular exercise prescription and monitoring tool for rehabilitation and high-performance sport settings because of the feasibility of use in a real-world setting. It is important to note that implementation of RPE should include standardized instructions and anchoring to ensure that individuals understand how to use the scale (Valentino et al., 2022; van der Scheer et al., 2017), especially given the dissonance in the interpretation of RPE between healthcare professionals and individuals with SCI (Jung et al., 2023). Prior to using RPE as an exercise intensity measure, anchoring procedures have been used to improve its validity (Lagally & Costigan, 2004). RPE has been demonstrated to have the capacity to demarcate moderate, heavy, and severe intensity domains in healthy participants (Bok et al., 2022). During the development of the RPE scale, Dr. Gunnar Borg determined the objective physiological reference for the RPE scale was the heart rate of healthy young male participants exercising on a leg cycle ergometer (Borg, 1962). Other research has suggested that breathing and sensations of strain from the muscles are related to how non-disabled populations feel during exercise (Cafarelli, 1977, 1982; Chen et al., 2002), however there is little known about the body sensations and perceptions that individuals with SCI use to anchor and differentiate varying intensity levels. The purpose of this research was to examine both the perceptions of exercise intensity and the use of an RPE scale for rating exercise intensity in individuals with SCI and their healthcare professionals. Based on the principles of co-production research (Bochkezanian & Anderson, 2022; Smith et al., 2023), we ensured the individuals with lived experience were consulted throughout the research process and data collection (Figure 1). We involved healthcare professionals to provide some insight about how exercise intensity is prescribed and monitored during supervised exercise training in the early stages of rehabilitation after an SCI.

4.3 Methods

This cross-sectional, qualitative, descriptive study used semi-structured interviews to understand the experience of exercise intensity from the perspectives of individuals with SCI, and healthcare professionals specializing in SCI rehabilitation. This study was approved by the Hamilton Integrated Research Ethics Board for Study 1 (#14074) and Study 2 (#14023). Figure 1 depicts Study 1 and Study 2 as well as the stages within each. Verbal or written consent were provided for Study 1 and signed informed consent was obtained at time of data collection after the risks were explained for Study 2.

Research Setting and Participant Recruitment

For study 1, individuals with lived experience with SCI or healthcare professionals were recruited. The eligibility criteria were as follows: 1) a traumatic SCI and 2) experience with physical rehabilitation and/or exercise, or 1) licensed healthcare professional that supports physical activity and/or functional movement and 2) worked in a setting that focuses on individuals that have a traumatic SCI. All interviews were conducted in English.

We recruited 20 participants through the Physical Activity Centre for Excellence at McMaster University, and the Regional Rehabilitation Centre in Hamilton, Ontario. The sample size was established using the criteria for information power, a concept for determining sample size in qualitative studies (Malterud et al., 2016). We prioritized the voices of the individuals with lived experience with a traumatic spinal cord injury. All healthcare professionals worked in the settings which the individuals with SCI were recruited and may have played a role in their experiences, however we were unable to confirm the role of the health care professionals in the care of any individual participants due to participant confidentiality. Therefore, we aimed to recruit at least 50% of the study participants as individuals with SCI, with the remaining proportion comprised healthcare professionals. 15 individuals with a traumatic SCI and 5 healthcare professionals were interviewed from August 2022 to February 2023. Two interviews were completed over Zoom, four interviews were completed over the phone, and 14 interviews were completed in-person at McMaster University in a private meeting room.

For study 2, we recruited 18 participants through the previously indicated settings. 16 new participants were recruited, and two participants completed both study 1 and study 2. A sample size of 17 participants was determined via a power calculation for the primary outcome, ratings of perceived exertion, based on a previously published study (Satia et al., 2020) Participants were eligible if they met the eligibility criteria for study 1, in addition to the following: 1) used a manual wheelchair for 50% of their waking time, 2) were at least 6 months post-traumatic SCI, 3) able to complete arm cycling high intensity exercise, and 4) willing and able to attend McMaster University. Participants were ineligible if they had a recent diagnosis of secondary disease (<6 months) or unmanaged autonomic dysreflexia and/or orthostatic hypotension.

Data Collection

Data collection and data analysis occurred simultaneously, and recruitment continued until no new themes arose, termed data saturation. The semi-structured interviews were conducted either online through video-calling, phone call with audio recording or in person at mutually convenient location for a duration of 1hr-1.5hrs. The participants were given the choice of interview setting to attend to their privacy, confidentiality, and accessibility needs. One team member led the interviews based on a semi-structured interview guide (see Table 2) and maintained a reflective journal. The journal, and subsequent discussions with the other team member, were used as a tool to reflect on the interview process, including how questions were delivered and received. The information documented in the researchers' journal was used to encourage researcher reflexivity, and for analysing the relationships between meanings given to certain concepts during fieldwork and the academic meanings later given to those concepts extracted from the conversations (Pink, 2014). At the end of the interview, participants completed a demographic questionnaire including a characterization of their physical activity, whereby individuals with SCI completed the Leisure Time Physical Activity Questionnaire for people with SCI (Martin Ginis et al., 2021) and healthcare professionals completed the International Physical Activity Questionnaire (Craig et al., 2003). All interviews were audio-recorded. The recordings were processed using automation transcription software (Otter.ai; California, United States) and the transcription was then revised manually by one team member directly after the interview to increase the accuracy of the transcription to exclude errors and include pauses. The transcription was then reviewed by a second team member. Privacy and anonymity considerations, such as the security of the data and the risk of security breach, were clarified for participants prior to study enrolment and the use of online automatic software.

During study 2, participants were given standardized instructions and familiarization to the 0-10 category ratio (CR10) ratings of perceived exertion scale (Borg, 1982). Participants completed a maximal exercise test on an arm cycle ergometer. Individuals rated both their central RPE and arm RPE at each stage of the maximal exercise test until exhaustion. The limiting factor of the maximal exercise test was recorded as the RPE with the highest rating at the time of exhaustion. Participants reflected on their experiences after completing the exercise and reported one word and a body sensation description corresponding to each level of the RPE scale, based on semi-structured questions in Table 2.

Data Analysis

For analysis, we used an interpretive approach, which is an inductive analytic approach to understand the clinical and exercise experiences and produce clinical recommendations (Thorne et al., 2004). Transcripts were uploaded to qualitative coding software using MAXQDA (Version 22.4.0; MAXQDA Plus 2022; Berlin, Germany). Interim team coding was conducted on the first five transcripts, by hand, for as many patterns as possible, including extracts of the data within each code, to provide context (Braun & Clarke, 2006). Feedback between the researchers was conducted to ensure the interviews were addressing the research questions. Each set of 5 transcripts thereafter were individually coded and reviewed by both researchers for discrepancies and inclusion, or exclusion, of codes based on our research questions. For example, we found some participants used monitoring technology to gauge their exercise intensity (i.e., Apple watch or exercise equipment screen). In addition to tracking their workouts, monitoring technology might influence or alter their experience of body sensations and therefore questions about monitoring technology were included for all participants thereafter. All transcripts from interviews with healthcare professionals were team coded to ensure both researchers were aligned on the categorization of the healthcare professional's perspectives. Researcher judgment was used to determine the extent to which a theme and/or reoccurring pattern captured a sentiment that was important to the experience (Braun & Clarke, 2006). For example, a participant indicated they felt "tiredness", however after being probed about where in their body they felt that sensation, they described it as "arm tiredness and heaviness after exercise", we coded this as muscle fatigue rather than general fatigue. Once the data was coded, the team broadly analyzed the data and collated codes into identified themes. Themes were determined using open, axial, and selective coding using grounded theory, whereby themes were derived from the data itself rather than from existing theory (Braun & Clarke, 2006). Themes were not determined exclusively by the frequency of words and phrases used because a larger number of occurrences does not necessarily determine significance (Braun & Clarke, 2006). To enhance credibility of results and to ensure that the interpretations of the findings were aligned with the data itself, community members with lived experience with SCI checked the transcribed data and themes, were included in the analysis and authorship of this research (Burke, 2016). Descriptive data was summarized using descriptive statistics.

4.4 Results

38 participants were recruited for this research including: 15 individuals with SCI (53 ± 20 years; 73% male), 5 healthcare professionals (47 ± 14 years; 100% female) for semi-structured interviews and 18 individuals with a traumatic SCI for in-person exercise testing and semi-structured interviews (48 ± 16 years; 83% male). Participant characteristics are summarized in Table 1.

The following two themes emerged from the four stages of data collection: 1) muscle sensations, as well as a combination of other sensations, are used to inform individuals with SCI and healthcare professionals about exercise intensity in community and supervised settings, and 2) RPE is generally not well understood by individuals with SCI and healthcare professionals, however, the utility and relevancy of the scale as a communication, and body awareness, tool is evident. Within these two themes, there emerged several subthemes for “muscles and other sensations during exercise” including: 1) muscle sensations, 2) combination of symptoms, 3) breathing, 4) heart rate, 5) temperature, 6) fatigue, and 7) dizziness. In addition, 2 people commented on mental activation during maximal exercise such as psychological attention and awareness directed towards completion of exercise. 2 people also suggested time as a reference for exercise intensity. For example, an RPE of 10 at maximum intensity can be held for 5 to 10 seconds and an RPE of 5 at a hard intensity can be held for 30 minutes. The one prominent emerging theme was that muscle sensations are the most salient perception for determining exercise intensity for individuals with SCI.

The subthemes for RPE understanding were: 1) RPE anchoring, 2) language misunderstanding, and 3) lack of RPE knowledge. Two suggestions regarding the use of RPE for individuals with SCI were to use less numbers (2 people) and potential substitutions for the word "severe" as it had a negative association (2 people).

The frequency of sensations associated with each level of the 0-10 RPE scale are presented in Figure 2. In this figure a total of 38 observations were summarized across Study 1 and Study 2. Four individuals out of 38 observations held alternate views of the RPE scale which altered their contribution to the sensation frequency chart. Based on our interviews in Study 1, one healthcare professional used functional movement goals as a marker of achievement, one healthcare professional used vitals and pain as a marker of intensity, and one participant did not use the RPE scale because they believed it was too subjective. Based on our post-exercise, semi-structured interviews in Study 2, one participant did not associate the sensations they described to numbers on the RPE scale, however they did talk about body sensations related to each of low, moderate, high, and maximum intensity. For the previously mentioned reasons, three participants did not have any observations from their interviews represented in Figure 2 and one participant only contributed to the maximum category.

After participants completed a maximal arm cycling exercise test, seven people out of 18 rated their arm RPE as highest, three people rated their central RPE as highest (anchored to breathing and heart rate), and 8 people rated their arm and central ratings (RPE) equally as limiting factors (Column 5, Table 3).

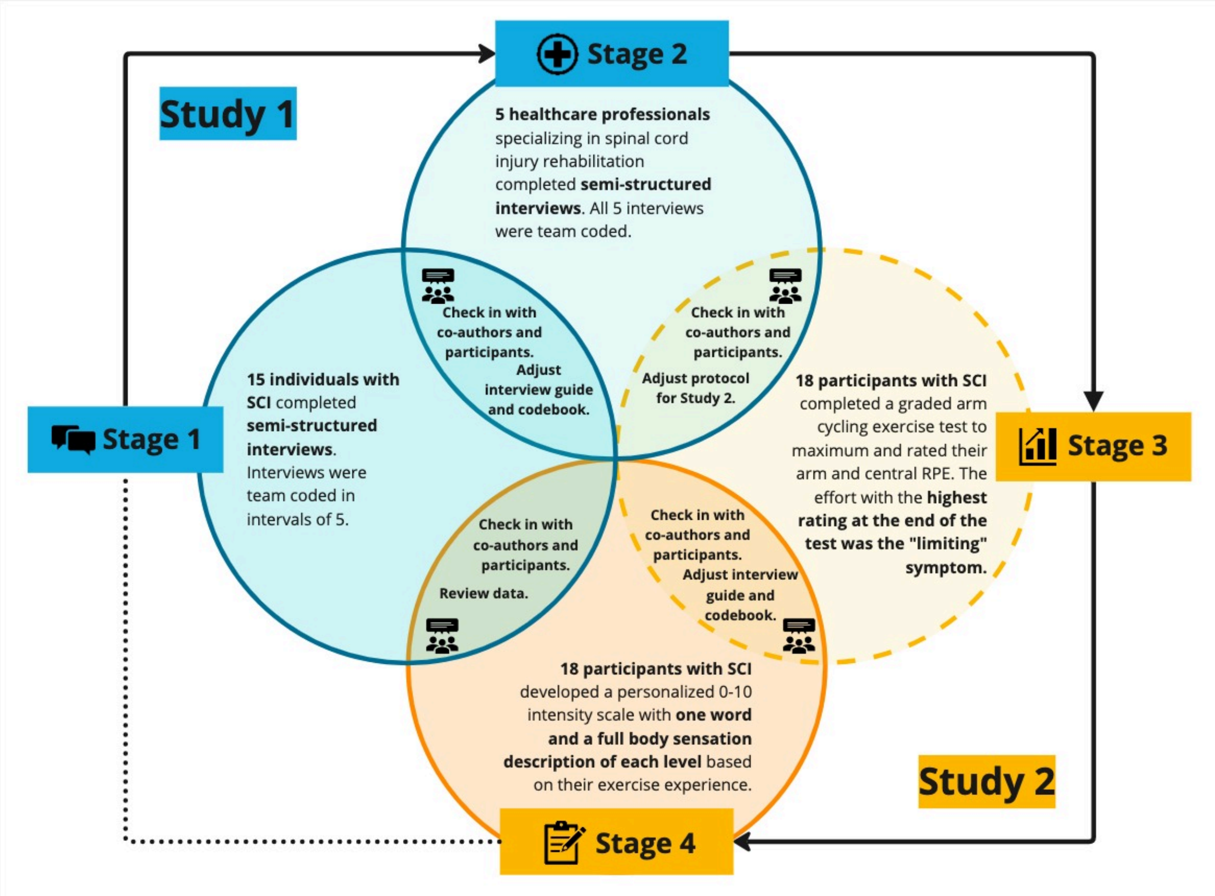

Figure 1. Graphic depicting the iterative data collection and analysis process divided into Study 1, Stage 1 and Stage 2, and Study 2, Stage 3 and 4. In between each stage, the data was reviewed with co-authors, including an individual with lived experience with SCI and a physician specializing in physical medicine and rehabilitation. The data collection involved quantitative and qualitative methods, whereby Stage 3 quantitative graded exercise testing RPE data was collected during an experimental set-up (dashed outline) and all other stages collected qualitative data via semi-structured interviews

(solid outline), respectively. Note: The primary and secondary outcome for Study 2 will be published as part of another study.

4.5 Discussion

This research captures the experience of exercise intensity in 38 individuals with SCI and five healthcare practitioners using a qualitative descriptive approach. The cumulative evidence suggests that in these individuals, muscle sensations are the primary anchor used for the determination of exercise intensity, in combination with secondary factors such as breathing, and fatigue, as the markers of exertion during varying intensity levels. In addition, the RPE scale has significant utility and is relevant as a communication and body awareness tool for individuals with SCI to use independently and with healthcare professionals for exercise prescription and monitoring during exercise.

Individuals described these muscle sensations as “muscle tension”, “muscle heaviness”, and “muscle tiredness”. There is some other data to suggest leg strength is associated with leg fatigue in ~38,000 non-disabled people referred for cardiopulmonary exercise testing (Satia et al., 2020) and that muscle strain measured by electromyography is related to exertion during exercise (Cafarelli, 1977, 1982; Chen et al., 2002), however these relationships are underexplored in individuals with SCI. Participants consistently described muscle sensations as a factor in determining their exercise intensity, whereby 35 out of 38 observations mentioned “muscle sensations” as part of the experience of 10 out of 10 on the RPE scale (Figure 2). Based on the data summarized in Figure 2, individuals had more sensations descriptions for RPE levels 3, 5, 8, and 10, with the number of body sensation descriptions increasing with higher exercise intensity. While there are many theories about perception, this research supports the cognitive constructivist approach, where multiple sensations are integrated to form the total experience (Piaget, 1968). Learning theories suggest that individuals give attention to the salient cues, and in addition, they cannot pay attention to what they do not perceive (Rumbaugh et al., 2007). We believe our research may serve as a guide to the number of options and cues that healthcare professionals use when guiding individuals through exercise rehabilitation after an SCI. We suggest that exercise intensity prescription should involve the description of symptoms (i.e., muscle tension and heaviness) rather than a classification of intensity (i.e., mild, moderate, vigorous intensity) to permit increased perception and attention by directing and anchoring. Participants often reported that they learned these cues on their own, however this research suggests that anchoring education and communication in the early stages of rehabilitation may provide individuals with SCI with a be a valuable skillset. Our study aligns with prior research and suggests muscle sensations may be the primary physiological intensity indicator associated with the RPE scale in individuals with SCI (Cafarelli, 1977, 1982; Satia et al., 2020).

It is important to note that exertion during exercise has been studied since the 1800s (Lagrange, 1898). In 1962, heart rate was used to determine workload during the development of RPE scale (Borg, 1962), however since the late 90s the RPE scale has also been used for monitoring exercise intensity in SCI rehabilitation and paralympic athlete settings. Both populations can experience altered heart rate responses to exercise due to the autonomic function disruption despite having a broad range of abilities. Typically, individuals with a traumatic SCI above the level of T6 typically have an altered heart rate response to exercise as one of many symptoms of autonomic dysreflexia (West et al., 2016). This research supports an alternate hypothesis that exertion, measured by the RPE scale, is most strongly related to muscle strength. The RPE scale provides an accessible and relevant tool for measuring exercise intensity.

Potential factors that impact the use of RPE scale

The potential factors that impact the use of the RPE scale can be summarized into three subthemes: 1) language misunderstanding, 2) influence of the experience of individuals with SCI with inpatient rehabilitation and their relationship with healthcare professionals, and 3) the disconnect between the common RPE scale descriptors and the body sensations experienced by individuals with SCI. We addressed these issues in Study 2 by introducing a familiarization with standardized instructions, asking participants to reflect on their experiences and perceptions during exercise, and capturing their opinions on how to individualize the RPE scale after they had completed exercising. Participants were often able to describe how 7 out of 10 levels of the RPE scale related to their own body sensation experiences. It seems the most valuable version of the scale is one that is developed and individualized by the participant. However, the process of completing standardized instructions, familiarization, supervised exercise, and a guided scale individualization is unrealistic. Rather, we propose the development of a new RPE scale that uses muscle sensations as the primary description of the RPE scale for use with individuals with SCI. Future research should aim to develop an SCI-specific RPE scale accompanied by visual descriptions, similar to the rating of fatigue scale, which can be used with and without instructions (Micklewright et al., 2017). The development of an RPE scale that is better suited for individuals with SCI, who are often cited the lowest active clinical population on the physical activity spectrum (van den Berg-Emons et al., 2010), may also lead to improved application of RPE scales for other populations that experience barriers to physical activity participation.

4.6 Limitations

This research is not without limitations. First and foremost, wheelchair users experience many physical and sociocultural barriers to exercise participation (Levins et al., 2004) that are not addressed by this research. In addition, most of our sample either engaged in rehabilitation or worked at the Regional Rehabiliation Centre in Hamilton, Ontario, therefore, this study represents exclusively the sociocultural factors associated with this region and healthcare practices in Canada. Different clinical objectives and practices may exist in other hospitals and rehabilitation settings. While all participants with lived experience had a traumatic spinal cord injury, Study 2 had an eligibility criterion requiring at least 50% of waking time to be using a manual wheelchair that likely excluded individuals with a complete injury above C5 (level of the brachial plexus) that were included in Study 1. Future research may seek to examine the effect of level and completeness of spinal cord injury on the experience of exercise intensity. Previous research suggests that the physical activity delivered during inpatient rehabilitation plays a role in the functional potential and quality of life following SCI (Teeter et al., 2012) and this physical activity education is related to physical function long-term

(Baehr et al., 2022). Further research should examine in more detail the impact of physical activity education on long term physical activity adherence and behaviours around exercise in individuals with SCI.

4.7 Future Directions

Given that muscle sensations were the most salient sensation used to describe the level of exertion during, and reflecting on, exercise experiences, further research should be conducted to determine if muscle strength can predict RPE during exercise in this population. This research could be used for the development of an updated Canadian physical activity guidelines with exercise intensity prescription that includes a sensation description (i.e., muscles burning, fast pace breathing, heart rate increased) rather than a summary word (i.e., moderate intensity) and an updated RPE scale tailored for individuals with SCI. Additionally, in the current guidelines there is no exercise intensity recommendation for strength training for individuals with SCI, nor is there guidance on how to complete high intensity interval training, so these are other areas to consider in future versions.

4.8 Conclusion

Individuals with SCI and associated healthcare professionals were interviewed to reflect on their past experiences with exercise intensity and a second cohort exercised in a laboratory setting to further examine ratings of perceived exertion and develop individualized exercise intensity scales. Participants most frequently used muscle sensations, in combination with other sensations, to anchor each exercise intensity level of the RPE scale. This research suggests that the RPE scale is useful and relevant for individuals with SCI particularly when it can be personalized to an individual's physiological experience during exercise. The participant experiences provided guidance concerning the accessibility of education methods and tools used to prescribe exercise that can be implemented during SCI rehabilitation. This research will inform future physical activity guidelines and RPE scale development for individuals with SCI.

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Table 1. Demographic characteristics of participants.

	Study 1 - SCI *(n=15; 73% male)*	***Study 1 – Healthcare Professionals*** *(n=5, 100% female)*	***Study 2 - SCI*** *(n=18; 83% male)*
Age (yrs)	53 ± 20	47 ± 14	48 ± 16
Race, n (%)			
European/ Caucasian	**13 (87%)**	**5 (100%)**	**12 (66%)**
South Asian	1 (7%)	0 (0%)	1 (6%)
East Asian	1 (7%)	0 (0%)	1 (6%)
West Asian/North African	0 (0%)	0 (0%)	1 (6%)
Chinese	0 (0%)	0 (0%)	1 (6%)
Mixed:			
Caucasian & South Asian	0 (0%)	0 (0%)	1 (6%)
Caucasian & African	0 (0%)	0 (0%)	1 (6%)
Level of Injury, n (%)			
Paraplegia	6 (40%)		**9 (50%)**
Tetraplegia	**9 (60%)**		9 (50%)
Time since event (yrs)	10 ± 10		19 ± 15
Cause of injury, n (%)			
Medical related	**7 (48%)**		3 (17%)
Motor related	2 (13%)		**6 (33%)**
Fall related	2 (13%)		4 (22%)
Work related	2 (13%)		1 (6%)
Sports related	2 (13%)		3 (17%)
Violence related	0 (0%)		1 (6%)
Profession, n (%)			
Physiotherapist		**3 (60%)**	
Occupational Therapist		1 (20%)	
Kinesiologist & RMT		1 (20%)	
Physical Activity	*LTPAQ-SCI*	*IPAQ*	*LTPAQ-SCI*
Mild MET• hrs/week	119.7 ± 171.5	24.4 ± 27.2	54 ± 81
Moderate MET• hrs/week	14.5 ± 15.4	3.0 ± 4.2	21 ± 24
Vigorous MET• hrs/week	11.0 ± 21.9	9.2 ± 18.4	15 ± 25

Note. The criterion with the highest proportion is bolded within each category. IPAQ = international Physical Activity Questionnaire; LTPAQ-SCI = leisure time physical activity questionnaire for individuals with a spinal cord injury; MET = metabolic equivalent; RMT = registered massage therapist.

Table 2. Prompts and questions from the semi-structure interview guide in Study 1 and Study 2. The exact language used within each interview depended on the nature of the conversation.

Interview prompts
Study 1
Have you ever used a 0-10 rating system to gauge your intensity? To what extent did you have a clear sense of what each rating felt like? How did/does it affect your exercise experience? I would like you to tell me about what body sensations you are feeling as you go through a scale of 0 to 10, starting at zero equal to no exertion at all or your resting state, and ending at 10, equal to your maximal exertion you can achieve. What are the decisions that you make to get yourself to your maximum? What are some prior activities in your day that will influence this process of getting to a 10 out of 10? How do you decide how hard you are working?
Study 2
We used the 0-10 ratings of perceived exertion scale during your arm cycling exercise. We are looking to understand and redefine the scale using words and descriptions that are specific to you. Please talk through each number on the scale and describe body sensations associated with each level and use one word to summarize it. You can use the original ratings of perceived exertion scale for reference and discuss how you might alter the scale so that the scale is best suited to you. Please review the scale. Does this scale describe your exercise intensity experience? Feel free to make any adjustments or clarifications. Can you describe what type of exercise you were thinking of when you were redefining the exercise?

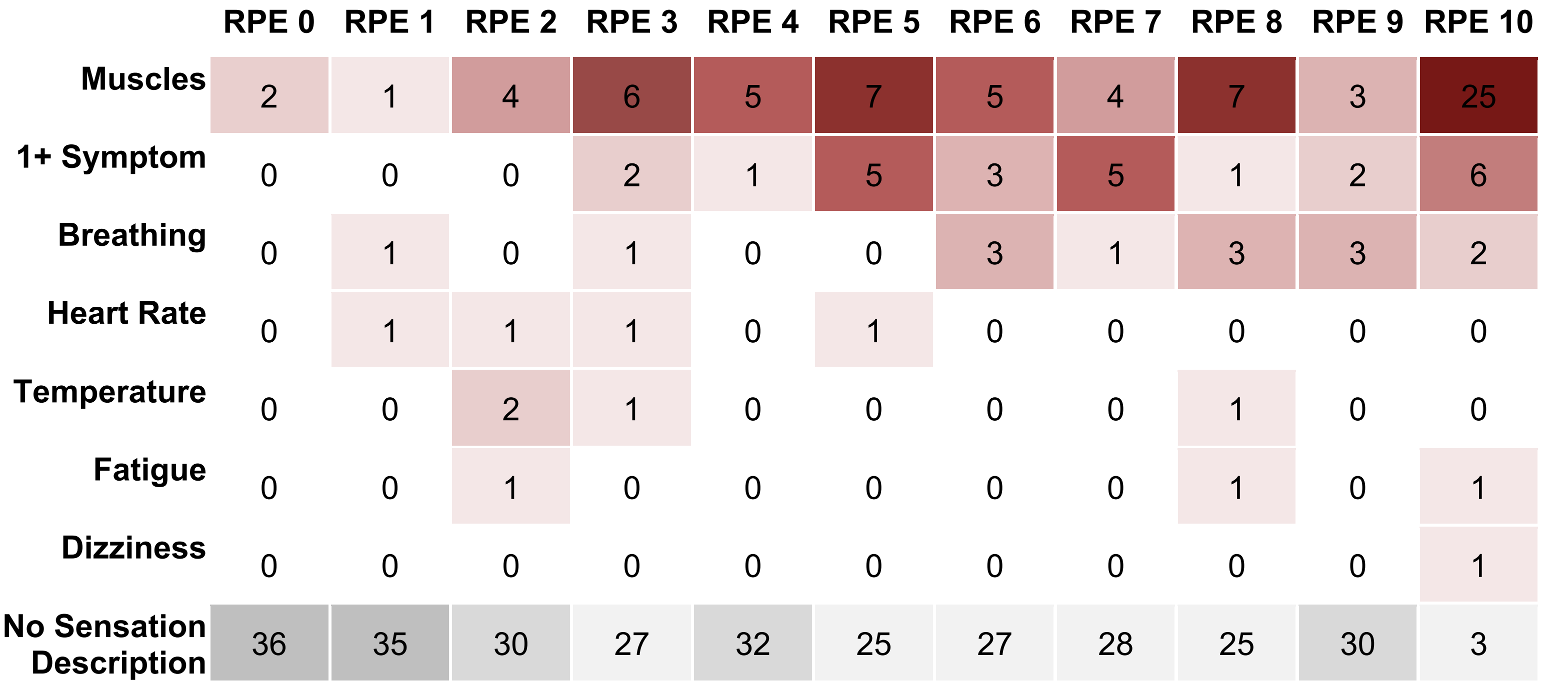
Table 3. Supporting participant quotes for Theme 1: muscles and other symptoms during exercise.

Theme	**Subtheme**	**Exemplary Quotes from Individuals with SCI (n=15, Study 1)**	**Exemplary Quotes from Healthcare Professionals (n=5, Study 1)**	**Summary from Maximal Exercise Test (n=18, Study 2)**	**Examples from Post-exercise RPE Scale (n=18, Study 2)**
Sensations and symptoms during exercise	Muscle sensations: - Muscle burning - Muscle tension - Muscle tiredness or heaviness	"Sometimes I just don't have like the muscle energy to push hard enough to get to like a nine or a 10. Which I want to but it's just that's just not wear I'm at so."	"Well sometimes if they're shaking, I know that it's really heavy for them."	7/18 rated their **arm RPE highest** after maximal exercise test completion	"RPE 10: Very hard, Maximum intensity – hitting the wall, arm strength nothing left"
	Breathing sensations	"And then when it's super intense, as a full muscle pretty hard to breathe."	"I feel like they're short of breath very, very quickly. And it's interesting to me that a lot of them don't recognize that they're short of breath."	3/18 rated their **central RPE highest** after maximal exercise test completion	"RPE 10: All out – breathing lungs start to burn"
	More than one sensation, equally limited by both.	"Extremely hard to breathe, and my muscles are still sore."	"Sometimes it's just like, they don't feel like they can go anymore. It doesn't, very rarely, to me looks like they're out of short of breath."	8/18 rated their **arm RPE the same as their central RPE** after maximal exercise test completion	"RPE 10: Hardly go anymore, thinking 'that's enough"
	Fatigue sensations	"And exhaustion, you just have to stop because you feel like you can't go anywhere."	"They're noticing, like, Okay. I'm, I'm hitting my, my max, kind of, like, I can't do as much more, either through that same range, or I'm like, just trying to get	N/A	"RPE 10: Max effort, just bonk, extreme exhaustion"

			this to happen. And it's like, not happening anymore, right? So yeah, I would say just kind of that like fatigue”		
	Temperature sensations	“I can't push outside right now, I could do a lap, but my hands get cold. I can’t do it.” –PAC22	None.	N/A	“RPE 8: Max, total exertion – temperature high”
	Dizziness sensations	“I would say I get a bit of like a head rush. But just like my head, I could feel this kind of not a headache, I don't know, it's kind of something in my head.”	“So, you know, a headache and feeling flush and sweating.”	N/A	“RPE 10: Maximum – very dizzy” “RPE 10: Maximum – vision changes, seeing white”
	Heart rate sensations	“Getting my heart rate up. It's good because my heart rates not always up sometimes, you know?”	“Do you feel like it's just because you're out of puff, because you're de-conditioned. And this is difficult exercise, you know, is your heart racing, like, those kinds of things that I'll ask and if I'm concerned about it, like I said, I'll put the monitor on them so that I can see what happens while they're exercising.”	N/A	“RPE 8 – Hard: Heart rate is increased”

Table 4. Supporting participant quotes for Theme 2: ratings of perceived exertion (RPE) understanding.

Theme	Code	Exemplary quotes from Individuals with SCI (n=15, Study 1)	Exemplary quotes from Healthcare Professionals (n=5, Study 1)	Examples from post-exercise RPE Scale (n=18, Study 2)
Ratings of perceived exertion (RPE) understanding	RPE Anchoring	“You heard from my perception of the scale, there's a certain point, I'm not going past that. So, if it's too much for me, I ain’t goin there.”	“You can just see in their mind. They're like, oh, it's like, you know, they're just picking a number out of nowhere.”	See Figure 2 for a summary of the body sensations used to describe each intensity level of the RPE scale.
	Language Misunderstanding	“I would agree with because I do struggle at times when they asked me where I want that on the scale. And I think four is like moderate and five is like, harder. And I just kind of run in that range. Because that seems to be the, in my mind the fit for where I'm at.”	“It's very hard to like, educate them on a scale. Because when I look at a scale, if I just looked at numbers, because if the words didn't mean a whole lot, to me, five would be like, Midway, and 10 would be like, my max, like 10 would be me, like failing on. Like my last rep, like I did. That was a 10, it was super hard. Like, and I failed on the last one, or whatever five to me would be a midpoint. I'm only half like, I'm only taking up half of what's in the tank.”	**2/18 participants** suggested less options or numbers on their scale. **18/18 participants** left at least 1 description blank on their individualized scale. 1**5/18 participants** suggested the word ‘severe’ had negative association and used words like ‘difficult’, ‘‘challenging’, ‘intense’ or ‘hard’ to describe 5-7 out of 10 on their individualized scales.
	No knowledge of RPE	“Um, I don't? I don't think so. Because when I was at rehab, I don't remember them ever having the numbers? No, yeah, they would just start off with whatever lightweights like sometimes in a group.”	“[During client intake,] we go in the office and I like to explain the RPE scale, I explained, we usually like you working about in like the three to five range at the beginning like on ours, like it says like, if you're novice like this is your kind of range to aim for, you're experienced, you can go a little bit higher.”	**17/18 participants** could clearly articulate at least three separate descriptions of body sensations on their individualized scales.



	RPE 0	RPE 1	RPE 2	RPE 3	RPE 4	RPE 5	RPE 6	RPE 7	RPE 8	RPE 9	RPE 10
Muscles	2	1	4	6	5	7	5	4	7	3	25
1+ Symptom	0	0	0	2	1	5	3	5	1	2	6
Breathing	0	1	0	1	0	0	3	1	3	3	2
Heart Rate	0	1	1	1	0	1	0	0	0	0	0
Temperature	0	0	2	1	0	0	0	0	1	0	0
Fatigue	0	0	1	0	0	0	0	0	1	0	1
Dizziness	0	0	0	0	0	0	0	0	0	0	1
No Sensation Description	36	35	30	27	32	25	27	28	25	30	3

Figure 2. The above gradient frequency chart displays the frequency of sensations (y-axis) that are associated with each level of intensity (x-axis) out of a maximum of 38 observations across Study 1 and Study 2. The colour intensity corresponds with the frequency, where the darkest red colour is the highest frequency and no colour is the lowest frequency. The gradient of red corresponds with sensations and gradient of grey corresponds with the no sensation description.

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The authors report there are no competing interests to declare.

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Data Availability Statement

The data may be made available upon request, pending approval by the institution's research ethics board.

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Chapter 5: Arm strength predicts peripheral ratings of perceived exertion during arm cycling exercise in individuals with spinal cord injury.

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5.1 Abstract

Background: Individuals with a spinal cord injury (SCI) are amongst the lowest on the physical-activity-spectrum. Recent studies have identified high intensity interval training (HIIT) as a safe and time-efficient alternative to moderate intensity continuous exercise training (MICT), typically prescribed using a percentage of maximum heart rate or peak oxygen uptake in a laboratory setting. Perceived exertion, quantified by Borg's ratings of perceived exertion (RPE) Category Ratio-10 scale (CR10), is a subjective method used to prescribe and monitor exercise intensity in individuals with an SCI. However, the physiological and psychological variables that contribute to RPE during arm cycling exercise are unclear. **Objectives**: The aim of this research was to evaluate the relationships between RPE and physiological indicators of RPE during an upper body cycling graded exercise test in a supervised setting. The secondary aim of this research was to examine the acute recovery response to RPE-guided HIIT and MICT in individuals with an SCI, with arm cycling exercise experience and non-disabled individuals, naïve to arm cycling exercise. **Methods:** 18 individuals with an SCI (15M/3F; 9PP/9TP; >1yr post-traumatic SCI) and 17 non-disabled individuals (9M/8F) completed a graded exercise test on an asynchronous arm cycle ergometer and a single session each of RPE-guided moderate intensity continuous and high intensity interval arm cycling exercise, in a randomized order. Measures of central and arm RPE, peak oxygen uptake, peak power output, heart rate, muscle strength, skin temperature, autonomic function, and questionnaires regarding mood, exercise enjoyment, exercise self-efficacy and preferences, and exercise recovery were conducted. **Results:** In individuals with an SCI, triceps strength and age were associated with central RPE while no relationships were observed with arm RPE. In non-disabled individuals, there were no relationships between any physiological or psychological variables and central or arm RPE. Tolerability was slightly more favourable for MICT in individuals with an SCI, all other variables in the recovery questionnaire were not different between RPE-guided HIIT and MICT exercise in either group. **Conclusions:** This research may be used to inform the use of RPE to prescribe and monitor exercise intensity in individuals with an SCI.

5.2 Introduction

The economic burden of worldwide physical inactivity was estimated to be $68 billion dollars in 2020 (Ding et al., 2016). Approximately half of Canadians meet the Canadian physical activity guidelines of 150 minutes of moderate to vigorous activity per week (Statistics Canada, 2021) while only 10% of individuals with a spinal cord injury (SCI) meet the SCI-specific physical activity guidelines. It has been established that an increase in peak oxygen uptake ($\dot{V}O_2$peak) by 3.5 mL/kg/min corresponds to a 13% reduction in the risk of all-cause mortality in non-disabled individuals (Kodoma et al., 2009). Recent studies and meta-analyses have identified high intensity interval training (HIIT) as a safe and time-efficient alternative to moderate intensity continuous training (MICT) in individuals with an SCI (Astorino et al., 2021; Koontz et al., 2021; Peters et al., 2021) and HIIT potentially addresses some of the barriers individuals with an SCI experience associated with meeting the weekly physical activity recommendations (Peters et al., 2023).

Typically, HIIT is prescribed using a percentage of maximum heart rate or $\dot{V}O_2$peak achieved during a graded exercise test in a laboratory setting. However, individuals with an SCI often experience alterations in their heart rate response to exercise due to changes in autonomic function. Perceived exertion, quantified by Borg's ratings of perceived exertion (RPE) scale, is a subjective method used to determine exercise intensity that was originally described to have associations to heart rate responses observed in young healthy men exercising on a cycle ergometer. In rehabilitation and sport settings, RPE is used as a quick, equipment free method to prescribe and monitor exercise intensity in individuals with an SCI. While RPE has already been validated as a method of exercise prescription in this population, the physiological and psychological variables that contribute to RPE have not been comprehensively examined during arm cycling exercise. There is a knowledge gap informing the use of RPE measured during a maximal exercise test for prescribing HIIT in individuals. The objectives of this study are two-fold: 1) to evaluate the acute relationships between RPE and physiological indicators of RPE during an arm cycling graded exercise test in a supervised setting; and 2) to gather information to inform the RPE guided prescription of MICT and HIIT for arm cycling in non-disabled individuals and community-dwelling individuals with an SCI.

Quadriceps strength, using a one repetition maximum (1RM) assessment, has a strong relationship with RPE in non-disabled populations completing a maximal exercise test on a leg cycle ergometer (Satia et al., 2020), therefore we hypothesized arm strength would be associated with RPE for arm cycling exercise in both groups.

5.3 Methods

This study was an acute cross-sectional study that employed a randomized, crossover design. Participants completed three separate experimental visits. Participants arrived hydrated and abstained from alcohol and vigorous exercise, for at least 24hr before testing and avoided caffeine and food within 2 hours of the visit. All experimental visits were scheduled at the same time of day. Visit 1 included completion of a participant demographics questionnaire, Profile of Mood States (POMS) questionnaire, an exercise enjoyment and preferences questionnaire (PRETIE-Q), the sit-up test (Currie et al., 2015; Tang et al., 2012), 1 maximum repetition (1-RM) of pull down (latissimus dorsi), seated row, overhead press, biceps curl, and triceps extension, and a maximal graded exercise test on an arm cycle ergometer. Visits 2 and 3 were RPE-guided MICT or HIIT exercise on an arm cycle ergometer and additional questionnaires (POMS before exercise and the over-the-phone recovery questionnaire after exercise). Visits 2 and 3 were conducted in a randomized order using a web tool (https://www.graphpad.com/quickcalcs/randomize1/). This study was approved by the Hamilton Integrated Research Ethics Board (#14023). Written and signed informed consent was obtained after the risks were explained and the Get Active Questionnaire was completed prior to exercise testing (Canadian Society for Exercise Physiology, 2017; Petrella et al., 2018).

Participants

Participants were recruited from McMaster University, the Regional Rehabilitation Centre at Hamilton General Hospital, the Physical Activity Centre of Excellence, and the

Stay Well program at St. Joseph's Hospital. Non-disabled participants were included if they were 18 years or older, able to walk unassisted, had no previous experience with arm cycling, and were recreationally active. Participants using a wheelchair were recruited if they had a mobility impairment due to a chronic traumatic SCI (>12 months post-injury), used a hand-rim propelled wheelchair for over 50% of their daily waking time, and were willing and interested to attend McMaster University for all experimental visits. Participants were excluded if they had a history of cardiovascular or metabolic disease. They were also excluded any other emotional, physical, or mental health impairments that would have impacted their ability to complete the study. Participants were also excluded if they had unrecovered upper extremity injuries that inhibited their ability to complete arm cycling, required assisted breathing, were highly susceptible to autonomic dysreflexia or orthostatic hypotension, exercise-induced hypotension and/or autonomic dysreflexia, recent hospitalization, or any other condition deemed a contraindication by a physician.

Sample Size

For the sample size calculation, we used a retrospective analysis of a dataset examining the physiological variables predictive of cycling RPE in individuals referred for cardiopulmonary exercise testing (Satia et al., 2020). A power calculation was performed using 80% power with an alpha criterion of 0.05 for a regression predicting leg cycling RPE during cardiopulmonary exercise testing. The previously obtained full model R^2 of 0.6694 contained two variables (leg cycling power, cycling maximum power output) and the reduced R^2 of 0.4831 contained one variable (leg cycling power). The sample size was 17 individuals. Given that we were recruiting both non-disabled individuals and individuals with an SCI, we determined a sample size of 17 individuals per group (34 individuals total).

Data Collection

Primary outcome measure

Perceived exertion was measured using Borg's CR10 scale (Borg, 1982). Participants were familiarized with how to rate their exercise intensity as follows: they were provided with time to read the scale, and listen to standardized instructions, before resting RPE values were collected. During exercise, participants were asked for two RPE values in response to the following two questions: "What is your central RPE (chest and breathing)?" for central RPE, "What is your arm RPE?" for arm RPE.

Secondary measures

Participants anthropometrics were measured using a stadiometer for height and standard scale for weight for non-disabled participants and using a tape measurement of the participants in supine position for their height and a wheelchair accessible scale for individuals with an SCI. Self-report questionnaires were completed including a participant demographics questionnaire, POMS questionnaire, exercise self-efficacy, exercise enjoyment and preference and tolerance for exercise intensity (PRETIE-Q) questionnaires, and the over-the-phone recovery questionnaire. The POMS is used to describe transient and distinct mood states based on an individual's personal assessment for the past week, including the current day (McNair et al., 1971). Mood state has previously been linked to the perceptual continuum of RPE during leg cycling exercise (Eston & Parfitt, 2007). Participants with an SCI were asked to complete the SCI Exercise Self Efficacy Scale (Kroll et al., 2007). Non-disabled individuals completed a separate self-efficacy questionnaire (Jung et al., 2014). Perceived enjoyment was measured using the exercise enjoyment questionnaire (Kendzierski & DeCarlo, 1991). The PRETIE-Q was developed to quantify how participants internalize different exercise intensities (Ekkekakis et al., 2005). The over-the-phone recovery questionnaire that was developed based on concerns about HIIT described in previous qualitative research in individuals with an SCI conducted in our lab and a combination of questions from previous literature that have examined the tolerability, feasibility, and enjoyability high intensity interval training (Astorino et al., 2021; Koontz et al., 2021; Tanhoffer et al., 2012; Vestergaard et al., 2022).

Muscle strength testing was completed on a wheelchair accessible weight training machine (Equalizer Multi-Station, Equalizer Exercise Machines, Red Deer, AB, Canada) for the latissimus dorsi pulldown (lat pulldown), seated row, and overhead press, and using unilateral wall pulleys (Endorphin Pulleys, Patterson Medical Supply, Mississauga, ON, Canada) for the biceps curl and triceps extension. Non-disabled participants used a chair to complete the 1RM on the same machines. 1RM was assessed for a variety of upper body exercises, in the following order: lat pulldown, seated row, overhead press, biceps curl and triceps extension. Sufficient rest between exercises was provided to minimize the potential influence of muscle fatigue (Pelletier et al., 2016). 1RM was defined as the weight when failure occurred after subjects lifted progressively heavier loads through full range of motion.

The task, effort, and awareness scale measures the magnitude of the psychological sensations of effort and the extent to which the participant is consciously aware of the sensations (Swart et al., 2012). The task, effort, and awareness scale was measured at the beginning and end of the maximal exercise test (Visit 1) and the RPE-guided exercise bouts (Visits 2 and 3). The feeling scale, more commonly described as affective valence, measures feelings of positive or negative affect on a continuous scale ranging from -5 to +5 (Hardy & Rejeski, 1989). Feeling scale measures were collected at each stage of the maximal exercise test (Visit 1) and at the end of each interval of the RPE-guided HIIT session and at the end of each 10-min block of the RPE-guided MICT (Visit 2 and 3).

Skin temperature was measured using skin thermistors placed at standard anatomical landmarks on the forearm, chest, thigh, and calf to establish an estimate of mean body temperature during exercise (Ramanathan, 1964; Sanchez-Jimenez et al., 2022). Thermistors were attached to the skin using narrow strips of water-permeable surgical tape (3M Transpore) (Goss et al., 1989; Price & Campbell, 2002).

Participants with an SCI who were willing to transfer completed the sit-up test that provides a practical bedside assessment for orthostatic hypotension and autonomic function measurement that requires minimal equipment (Currie et al., 2015). 2 participants were unwilling to transfer and alternatively completed resting blood pressure in a seated position after 5 minutes of rest. For the sit up test, supine blood pressure was measured using automatic brachial artery oscillometry at the beginning of the visit 1 after 5 minutes of supine rest (Dinamap Pro 300 V2; GE Healthcare, Milwaukee, WI, USA). For the baseline supine BP, measurements were taken in triplicate with at least 1 minute in between each measure and then averaged. Orthostatic hypotension is defined as a drop in systolic blood pressure of 20 mmHg and/or a drop in diastolic blood pressure of 10 mmHg after passive movement from supine to seated position (Freeman et al., 2018) and is a surrogate for autonomic completeness. To assess orthostatic hypotension, discrete brachial blood pressures were taken every minute from the right arm using an automatic brachial oscillometry (Dinamap). The test began with 5 minutes of supine blood pressure measurements, after which participants were passively moved to the sit-up position over a 45-second time period. Thereafter, participants remained in a supported seated position while blood pressure and heart rate measurements were recorded for an additional 5 minutes. Supine and seated blood pressures and heart rates were reported as the average across each 5-minute interval. The maximum change in systolic blood pressure (ΔSBP) was calculated as ΔSBP = minimum seated SBP-average supine SBP, while the maximum change in diastolic blood pressure (ΔDBP) was calculated as ΔDBP = minimum seated DBP-average supine DBP.

Exercise Interventions

To measure $\dot{V}O_2$peak, participants completed a symptom-limited maximal graded exercise test using an asynchronous arm cycle ergometer (Lode B.V., Groningen, the Netherlands). Expired gases were collected throughout the duration of the exercise test to determine respiratory equivalent ratio (RER), oxygen uptake ($\dot{V}O_2$), carbon dioxide expiration ($\dot{V}CO_2$), and ventilation (VE) (Quark CPET; Cosmed, Pavona, Italy). Resistance was increased by 10 W each minute for all participants; however, the starting wattage was modified based on group (0W for SCI and 20W for non-disabled individuals). Participants were instructed to continue until volitional fatigue, or until they are unable to maintain a cadence of 40 rpm. All participants completed a verification phase 10 minutes after the completion of the maximal graded exercise test. During the verification phase, participants maintained the power achieved at the last completed stage of the arm cycling graded exercise test for as long as possible, until volitional exhaustion. Peak power output was defined as the greatest resistance achieved and maintained for at least 10 seconds during the maximal graded exercise test (Pelletier et al., 2015). The peak values achieved during the verification phase were compared to the peak values during the maximal graded exercise test and the relative $\dot{V}O_2$peak achieved during the verification phase was used as the $\dot{V}O_2$peak only if it was higher than the relative $\dot{V}O_2$peak of the maximal exercise test. In all other cases where the maximal $\dot{V}O_2$ achieved during verification phase was lower or the same as that during the graded test, the verification phase served as confirmation that the maximal graded exercise test generated a peak value. To measure heart rate, participants were fitted with a chest-worn heart rate strap throughout the duration of the testing visit (Polar Electro, Lachine, QC, Canada). Peak heart rate was defined as the greatest value achieved in a 5-second interval during the maximal graded exercise test.

RPE-guided HIIT sessions began with 4 min of light intensity arm cycling [RPE 2; corresponds with “slight” descriptor on RPE scale (Borg, 1982)], for a total of 17.5 minutes. For the HIIT block, participants performed a total of 4 intervals of 30 seconds of “all out” arm cycle ergometry [RPE 7; corresponds with “very severe” (Borg, 1982)] interspersed with 4 minutes of recovery [RPE 2; corresponds with “very slight” (Borg, 1982)]. RPE-guided MICT consisted of a total of 30 minutes of exercise. Participants performed a total of 28 minutes of arm cycle ergometry at moderate intensity [RPE 4; corresponds with "somewhat severe" (Borg, 1982)] at a self-selected cadence. All sessions ended with a 2 min cool down of light intensity arm cycling [RPE 2; corresponds with "slight" descriptor on RPE scale (Borg, 1982)]. Both protocols were based on a previous exercise training study in individuals with an SCI (Graham et al., 2019). After Visits 2 and 3, participants completed the over-the-phone recovery questionnaire.

Data Analysis

Means and standard deviations are summarized for each group (non-disabled individuals and individuals with an SCI). Normality was assessed using Shapiro-Wilk test and visual inspection using a histogram to confirm. Homogeneity of variance was assessed using the Breush-Pagan/Cook-Weisberg test and visual inspection using a residual vs. fitted plot to confirm the analysis. Data was analyzed using a stepwise linear regression to determine the physiological variable that was most predictive of arm RPE and central RPE. The alpha criterion was set *a priori* to a *p*-value to 0.05. All analyses were conducted in STATA/IC version 16.1.

5.4 Results

Our cohort of 35 individuals consisted of 18 individuals with an SCI (15M/3F; 9PP/9TP; >1yr post-traumatic SCI) and 17 non-disabled individuals (9M/8F). One participant with an SCI withdrew from the study after Visit 1 due to time constraints. 17

individuals with an SCI and 17 non-disabled participants completed a single session each of RPE-guided MICT and HIIT arm cycling exercise, in a randomized order. Participant demographics and physiological measurements at baseline, and at the peak of an arm cycling maximal graded exercise test are shown in Table 1. Age, 1RM lat pulldown, and $\dot{V}O_2$peak were different between individuals with an SCI and non-disabled individuals.

Potential independent contributors to the observed variance in peak central RPE in individuals with an SCI included in a forward stepwise linear model were age, height, weight, sex, 1RM lat pulldown, 1RM triceps extension, 1RM biceps curl, total mood disturbance (measured by POMS), peak task, effort, awareness scale, and affective valence (measured by peak feeling scale). Age and triceps strength contributed to peak central RPE (R^2=0.636, see Table 2).

Potential independent contributors included for peak arm RPE in individuals with an SCI were age, height, weight, sex, 1RM lat pulldown, 1RM triceps extension, 1RM biceps curl, total mood disturbance (measured by POMS), peak task, effort, awareness, and affective valence (measured by peak feeling scale). Peak feeling contributed to peak arm RPE (R^2=0.353; see Table 2). In a secondary analysis, we found age and muscle strength were not related in this dataset (r=-0.23).

Potential independent contributors to the observed variance in peak arm RPE and peak central RPE in non-disabled individuals included in a forward stepwise linear model were age, height, weight, sex, 1RM lat pulldown, 1RM triceps extension, 1RM biceps curl. No physiological or psychological variables contribute to central or arm RPE in individuals without SCI (Table 3).

There were no differences in feasibility, enjoyability, and recovery between HIIT and MICT in both individuals with an SCI and non-disabled individuals as shown in Table 4. Tolerability was better for MICT compared to HIIT in individuals with an SCI, more favorable for MICT likely because it is what most individuals with SCI are comfortable with and poses less consequences following exercise that may inhibit their daily activities. Examination of the arm strength measures using Pearson r were completed for both individuals with an SCI and non-disabled individuals in Tables 5 and 6, respectively. There was a strong relationship between all arm strength measurements in both populations.

5.5 Discussion

In this study, our main finding was that arm strength is a significant determinant of peak arm cycling RPE in individuals with an SCI. While individuals can use subjective ratings of exercise intensity to inform their exercise training, clinical populations, including individuals with an SCI, have altered heart rate responses to increases in exercise workload. Sensations that arise in the peripheral muscles, such as the muscles required to breathe and to cycle, all share the same sensory properties. The primary afferents communicate upward signals and culminate in the insula that give rise to body sensations such as pain, temperature changes, and itching (Craig, 2002). This research aligns with previous work in individuals with an SCI, where it was determined that the role of afferent feedback is to drive effort perception during exercise and physical stress (Paulson et al., 2014). When exercising, these pathways contribute to the perceived exertion. During exercise perceived exertion increases with increasing workloads until the point at which an individual is unable to tolerate exercise.

RPE in individuals with an SCI

We found that both age and triceps strength predicted peak central RPE in individuals with an SCI. This research aligns with previous work in non-disabled individuals that completed cardiopulmonary exercise testing on a leg cycle ergometer (Cafarelli, 1982; Satia et al., 2020). Given the relationship with age and strength, we completed a secondary analysis and found age and muscle strength were not related in this dataset (r=-0.23). Theoretically, there is a well-documented relationship between muscle strength and age, whereby muscle strength increases with age up until physical maturation (~18 years old) and decreases with age-related changes in muscle breakdown above the age of 40 (Keller & Engelhardt, 2019). Given that age is non-modifiable risk factor, we have primarily focused on examining the observation of a significant relationship between RPE and triceps strength. The two most active muscle groups during the arm cycling motion are the triceps brachii and biceps brachii muscle groups (Chaytor et al., 2020). However, research on the shoulder mechanics and wheelchair propulsion has shown there is a discrepancy in the ratio of activation of the biceps and triceps muscle groups based on the level of spinal injury (Gil-Agudo et al., 2010). We tested the predictive capacity of all muscle groups, however only triceps were predictive and additionally, the triceps are theoretically the most important muscle group to include based on the biomechanics of the arm cycling motion. Based on the current literature on wheelchair propulsion, we suggest that our finding that the triceps were the only muscle group predictive of RPE was because the triceps are highly active during arm cycling and their degree of activation is also related to the level of injury (Gil-

Agudo et al., 2010). In contrast, people with and without an SCI completing wheelchair propulsion exercise found no difference based on propulsion experience, whereas changes in frequency and intensity altered metabolic cost and efficiency in both groups (Lenton et al., 2008). Future research may wish to examine the impact of level and completeness of SCI on RPE and the relationships to strength of different muscle groups and exercise modalities.

Affective valence, measured by peak feeling scale, predicted arm RPE in individuals with an SCI. This finding is corroborated by previous work that shows that psychological factors, specifically mood, are related to perceived exertion (Halperin & Emanuel, 2020). It has been well documented that diurnal variations in RPE are in part due to mood in non-disabled populations (Gil-Agudo et al., 2010; Kunorozva et al., 2014; Vitale et al., 2013). Participants that rated their affective valence, measured by the peak feeling scale, as more positive had higher arm RPE at the end of the maximal exercise test. This is corroborated with the previous findings that suggest participants that report lower affective valence are less likely to continue exercising over time (Ekkekakis et al., 2011; Rhodes & Kates, 2015; Williams et al., 2008). Based on previous research, our findings are aligned whereby mood, exercise intensity, and RPE are all related (Gil-Agudo et al., 2010; Vitale et al., 2013).

RPE in non-disabled individuals

We found no physiological or psychological variables collected in this study that predicted peak central or arm RPE in non-disabled individuals. All non-disabled participants were naïve to arm cycling and therefore, the process by which they integrated the psychological experience of learning a new exercise may be through an alternate process compared to the participants with an SCI. While the end of the maximal arm cycling test was rated as 8 or higher out of 10 (“very hard”) for all the non-disabled individuals and they stopped the test based due to volitional exhaustion, it is unlikely that arm cycling exercise was limited centrally. Muscle groups associated with the arm cycling motion are smaller relative to the muscle groups associated with leg cycling, and arm cycling exercise is not likely to be limited by central capacity in non-disabled individuals (Andersen & Saltin, 1985; Richardson et al., 1993). Non-disabled participants may have experienced unique sensations alternate to their usual model of “maximal” exercise training. There is a greater psychological influence in non-disabled individuals that fits a paradigm alternate to the hypothesis in individuals with an SCI. An alternate hypothesis common in the field of exercise psychology is based on the existence of efference copies that refer to the internal duplicates of movement-producing neural signals (Vallortigara, 2021). Their primary function is to predict, often suppress, the sensory consequences of willed movement (Vallortigara, 2021). The non-disabled participants may have based their experience of exercise on maximal exercise tests completed larger muscle mass such as running or cycling and therefore the physiological consequences of arm cycling exercise may have been unrelated to their perceived exertion measured by RPE. Despite our findings, it has been shown that non-disabled participants have an increased $\dot{V}O_2$peak after RPE-guided arm cycling training (Hutchinson et al., 2023). The findings of our research may have been different had our participants had previous experience with arm cycling and we hypothesize arm strength would then predict RPE in non-disabled participants trained in arm cycling.

An alternate justification for the lack of relationship between RPE and the measured variables is based on the sample size calculation. This research study was informed based on a sample size calculation using data from a study that involved non-disabled individuals that completed a cardiopulmonary exercise test on a leg cycle ergometer (Satia et al., 2020). Based on the metabolic requirements of arm cycling in non-disabled participants, this mode of exercise should not be limited by central limitations as previously described. Additionally, the lack of standard criteria available to determine the end point of an arm cycling graded exercise test may explain the lack of an observed relationship between physiological variables and RPE. In this study, we based the termination of the maximal arm cycling exercise graded exercise test on participant volitional fatigue and the comparison with the verification phase, however for maximal exercise testing completed on a leg cycle ergometer, peak can be determined based on maximal heart rate, plateau of the $\dot{V}O_2$ curve, and achievement of an RER of 1.1 or greater (Ross et al., 2016). Only recently have there been standards published for handcycling (synchronous arm pedaling) in male athletes with an SCI (Stephenson et al., 2021), however there are currently no defined criteria to determine the end of an arm cycling maximal exercise test and therefore there is likely more variability in the peak values achieved using an arm cycle compared to a leg cycle ergometer (see Appendix A).

Recovery after RPE-guided HIIT and MICT

In a recent study on individuals with an SCI, the prevalence of shoulder pain ranges from 36 to 76% of the SCI population, with the majority of individuals experiencing chronic symptoms (at least 3 months), likely due to the high amount of stress put on the joint for the purpose of rehabilitation and daily living (Akbar et al., 2015; Bossuyt et al., 2018; Larsen et al., 2021; A. Richardson et al., 2021). We developed the recovery questionnaire based on the concerns of individuals with an SCI around HIIT that were collected in a qualitative research study conducted in our lab (see Chapter 4). Tolerability of exercise interventions have been quantified in previous work examining the effects of exercise on cardiorespiratory fitness in individuals with lung cancer (Scott et al., 2021). Participants indicated they were hesitant about HIIT because it was not possible to achieve high intensity, they were concerned about impairment in daily living, and they would not enjoy it. While it has been shown that delayed-onset muscle soreness peaks in 48-72 hours post exercise in non-disabled individuals (Hotfiel et al., 2018), the muscle damage post-exercise is different for people with an SCI based on paralysis time and training status (Mayer et al., 1999). In the current study, tolerability was more favourable for MICT than HIIT in individuals with an SCI. All other components of our recovery questionnaire, including feasibility, enjoyability, and recovery were not different between exercise modes for both groups. Previous work found 4 weeks of engagement in these MICT and HIIT protocols led to improvements in aerobic capacity (measured by $\dot{V}O_2$peak) in individuals with an SCI (Graham et al., 2019). When we asked the participants with an SCI how they would change the HIIT protocol for their own personal use, we found individuals that had tried HIIT previously would prefer to complete additional sets, whereby one set is equivalent to one high-intensity and one low-intensity interval. Based on the feedback provided as part of the recovery questionnaire, the HIIT protocol is prescribed at an introductory level and is suited for participants with an SCI who are naïve to HIIT.

5.6 Limitations

Our participants were recruited from the Hamilton region and therefore the rehabilitation practices are reflective of regional medical standards. Our previous qualitative study on the experiences of exercise intensity during SCI rehabilitation included healthcare practitioners and we found that individuals with SCI were not prescribed HIIT during both inpatient and outpatient rehabilitation unless it was initiated by the patient. Healthcare practitioners in the Hamilton region have time and resource constraints that may limit the variety of exercise techniques and modalities that are provided to the SCI population and therefore results may be different in a region where HIIT is more commonly prescribed.

Our recruitment criteria broadly included individuals that used a manual wheelchair at least 50% of their daily waking time, however this includes individuals with tetraplegia (injury at the level of T2 or higher) that have an incomplete injury and may have some arm motor function to be able to arm cycle without intact dermatomes to receive sensory information. The discrepancies between triceps and biceps innervation ratio in individuals with tetraplegia compared to paraplegia may lead to altered physiological relationships within the group of participants with an SCI. Disaggregated demographic data between tetraplegia and paraplegia is described in the Appendix B.

5.7 Future Directions

Future research should aim to develop the strength training guidelines for individuals with an SCI. Recommendations on the intensity of strength training may support individuals with an SCI to participate in their activities of daily living. Additionally, RPE-guided HIIT arm cycle ergometry could be an alternative method that is time-efficient, low cost, and accessible for individuals with an SCI that may lead to improvements in physical health and wellbeing (Peters et al., 2021). Future exercise guidelines should include guidance on HIIT for SCI and the utility and relevance of RPE as a method to prescribe and monitor exercise intensity.

5.8 Conclusion

There is an urgent need for alternative exercise training and prescription methods for individuals with an SCI that address the physical and psychological barriers they face each time they engage in both HIIT and MICT. We found that arm strength and age are predictive of central RPE, and peak feeling scale predicts peak arm RPE during arm cycling exercise in individuals with an SCI. The variation in peak central and arm RPE coxuld not be predicted by any psychological or physiological variables measured in this study in non-disabled individuals. Healthcare practitioners may prescribe arm strength exercises to reduce subjective ratings of exercise intensity during the daily activities completed by an individual with an SCI.

Table 1. Demographic characteristics of participants.

Variables	*SCI (n=18; 16% female)*	*Non-disabled Individuals (n=17, 47% female)*
Age (yrs)	48 ± 16	25 ± 9
Height (cm)	175.5 ± 10.3	170.6 ± 8.4
Weight (kg)	75.6 ± 10.5	72.8 ± 13.4
BMI (kg/m^2)	24.3 ± 6.8	25.0 ± 4.2

Resting heart rate (bpm)	70 ± 12	62 ± 9
Resting BP, systolic (mmHg)	117 ± 19	115 ± 9
Resting BP, diastolic (mmHg)	69 ± 11	67 ± 8
Resting CRPE	1 ± 1	0 ± 0
Resting PRPE	1 ± 1	0 ± 0
Resting feeling scale	+3 ± 3	+2 ± 2
Total Mood Disturbance Scale	-17 ± 25	0 ± 23
Resting task, effort, awareness	-1.7 ± 3.2	-2.6 ± 2
Exercise self-efficacy	66 ± 56	93 ± 53
Exercise enjoyment	103 ± 31	79 ± 25
Exercise preference: Mod. Intensity	12 (66%)	9 (53%)
Exercise preference: High Intensity	6 (33%)	8 (47%)
Race, n (%)		
European/ Caucasian	**12 (66%)**	**8 (47%)**
South Asian	1 (6%)	4 (24%)
East Asian	1 (6%)	1 (6%)
West Asian/North African	1 (6%)	1 (6%)
Chinese	1 (6%)	0 (0%)
Southeast Asian	0 (0%)	2 (11%)
Mixed:		
Caucasian & South Asian	1 (6%)	0 (0%)
Caucasian & African	1 (6%)	0 (0%)
Level of Injury, n (%)		
Paraplegia	9 (50%)	
Tetraplegia	9 (50%)	
Time since event (yrs)	19 ± 15	
Cause of injury, n (%)		
Medical related	3 (17%)	
Motor related	**6 (33%)**	
Fall related	4 (22%)	
Work related	1 (6%)	
Sports related	3 (17%)	
Violence related	1 (6%)	
Arm strength (lbs)		
1RM lat pull down	99 ± 39	127 ± 36
1RM seated row	73 ± 28	89 ± 37
1RM overhead press	69 ± 43	105 ± 47

1RM bicep curl	23 ± 11	25 ± 12
1RM tricep extension	19 ± 10	24 ± 11
Absolute $\dot{V}O_2$peak (L/min)	1.18 ± 0.46	1.82 ± 0.67
Relative $\dot{V}O_2$peak (ml/kg/min)	16.10 ± 6.8	26.25 ± 7.10
Peak power output (Watts)	68 ± 29	97 ± 31
RQ	0.92 ± 0.22	0.99 ± 0.11
Peak heart rate (bpm)	130 ± 31	159 ± 26
Peak CRPE	8 ± 2	8 ± 2
Peak PRPE	8 ± 2	9 ± 1
Peak feeling scale	+2 ± 3	0 ± 2
Peak task, effort, awareness scale	9 ± 2	6 ± 3
Temperature		
Calf temp. (°C)	27.1 ± 2.0	28.4 ± 0.9
Thigh temp. (°C)	30.1 ± 1.8	30.7 ± 1.3
Chest temp. (°C)	32.0 ± 1.1	32.0 ± 1.7
Forearm temp. (°C)	29.7 ± 1.5	30.4 ± 0.9
Whole body estimation (°C)	30.0 ± 0.9	30.6 ± 0.6
Sit up test (mmHg)		
Average supine SBP	116 ± 20	115 ± 9
Average supine DBP	68 ± 11	67 ± 8
Average supine HR	72 ± 12	62 ± 9
Average seated SBP	120 ± 18	114 ± 9
Average seated DBP	70 ± 13	71 ± 9
Average seated HR	74 ± 13	68 ± 8
ΔSBP, Sit Up Test Response	-4 ± 14	-4 ± 3
ΔDBP, Sit Up Test Response	-1 ± 9	0 ± 4

Table 2. Regression summary table for predictors of ratings of perceived exertion (RPE) in individuals with an SCI. Variables considered for the model included: Peak power, age, sex, weight, 1RM triceps extension, 1RM lat pulldown, total mood disturbance, peak feeling scale, peak task, effort, and awareness scale, peak heart rate, and chest temperature.

<table>
<tr><th colspan="4">Summary of stepwise regression: Dependent variable = Central RPE
F (1,14) = 9.59, R^2=0.636, Adjusted R^2 = 0.569</th></tr>
<tr><td>Variable</td><td>β</td><td>95% Confidence Interval</td><td>P-value</td></tr>
</table>

Age	-0.123	-0.185	-0.061	0.001
Triceps	0.120	-0.221	-0.021	0.022
Constant	17.138	12.597	21.679	0.000
Summary of stepwise regression: Dependent variable = Peripheral RPE **F (1,14) = 7.64, R^2=0.353, Adjusted R^2 = 0.307**				
Variable	β	95% Confidence Interval		P-value
Peak Feeling Scale	-0.123	-0.185	-0.061	0.021
Constant	7.716	6.751	8.682	0.000

Table 3. Regression summary table for predictors of ratings of perceived exertion (RPE) in non-disabled individuals. Variables considered for the model included: Peak power, age, sex, weight, 1RM triceps extension, 1RM lat pulldown, total mood disturbance, peak feeling scale, peak task, effort, and awareness scale, peak heart rate, and chest/forearm temperature, respectively.

Summary of stepwise regression: Dependent variable = Central RPE **F (0,17) = 0, R^2=0.00, Adjusted R^2 = 0.00**				
Variable	β	95% Confidence Interval		P-value
Constant	7.529	6.637	8.422	0.000
Summary of stepwise regression: Dependent variable = Peripheral RPE **F (0,17) = 0, R^2=0.00, Adjusted R^2 = 0.00**				
Variable	β	95% Confidence Interval		P-value
Constant	9	8.45	9.56	0.000

Table 4. Recovery questionnaire

Variables	*SCI* *(n=17; 12% female)*	*Non-disabled individuals* *(n=17, 47% female)*

	HIIT	MICT	*P (ex.)*	HIIT	MICT	*P (ex.)*
Tolerability	13 ± 1	12 ± 1	0.02*	11 ± 2	10 ± 3	0.24
Feasibility	6 ± 1	5 ± 1	0.58	5 ± 1	5 ± 1	0.16
Enjoyability	5 ± 2	5 ± 3	0.77	7 ± 3	7 ± 3	0.25
Recovery	23 ± 3	22 ± 3	0.17	23 ± 3	23 ± 3	0.84

Note. HIIT = high-intensity interval training, MICT = moderate intensity continuous training. Paired samples t-test between exercise types within each participant group **P* <0.05.

Table 5. Pearson r correlations matrix between all 1-RM arm strength assessments in individuals with an SCI.

Variable	Lats	Row	Overhead	Biceps	Triceps
Lats	1.00				
Row	0.84	1.00			
Overhead	0.97	0.87	1.00		
Biceps	0.81	0.88	0.83	1.00	
Triceps	0.96	0.84	0.96	0.71	1.00

Note. Data shown as Pearson correlation coefficients (r). Lats = 1-RM Latissimus dorsi pull down, Row = 1-RM seated row, Overhead = 1-RM overhead press, Biceps = 1-RM biceps curl, Triceps = 1-RM triceps extension.

Table 6. Pearson r correlations matrix between all 1-RM arm strength assessments in non-disabled individuals.

Variable	Lats	Row	Overhead	Biceps	Triceps
Lats	1.00				
Row	0.91	1.00			
Overhead	0.96	0.94	1.00		

Biceps	0.92	0.94	0.93	1.00	
Triceps	0.83	0.89	0.82	0.90	1.00

Note. Data shown as Pearson correlation coefficients (r). Lats = 1-RM Latissimus dorsi pull down, Row = 1-RM seated row, Overhead = 1-RM overhead press, Biceps = 1-RM biceps curl, Triceps = 1-RM triceps extension.

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Appendix A. Maximal arm cycling exercise test and verification phase values for both individuals with an SCI and non-disabled individuals.

Variables	*SCI (n=18; 16% female)*	*Non-disabled Individuals (n=17, 47% female)*
Highest Absolute $\dot{V}O_2$peak (L/min)	1.18 ± 0.46, n=18	1.82 ± 0.67, n=17
Highest Relative $\dot{V}O_2$peak (ml/kg/min)	16.10 ± 6.8, n=18	26.25 ± 7.10, n=17
GXT Absolute $\dot{V}O_2$peak (L/min)	1.18 ± 0.46, n=18	1.82 ± 0.67, n=17
GXT Relative $\dot{V}O_2$peak (ml/kg/min)	14.54 ± 9.91, n=18	24.67 ± 7.51, n=17
VER Absolute $\dot{V}O_2$peak (L/min)	1.26 ± 0.42, n=18	1.90 ± 0.55, n=16
VER Relative $\dot{V}O_2$peak (ml/kg/min)	15.68 ± 6.82, n=18	25.81 ± 6.67, n=16

Note. Highest $\dot{V}O_2$peak defined as highest relative $\dot{V}O_2$peak per participant, GXT = maximal graded exercise test, VER = verification phase.

Appendix B. Disaggregated demographic and strength data for the participants with SCI, separated into paraplegia and tetraplegia.

Variables	*Tetraplegia (n=9; 11% female)*	*Paraplegia (n=9, 22% female)*
Age (yrs)	49 ± 12	48 ± 20
Height (cm)	177.4 ± 9.2	175.5 ± 10.3
Weight (kg)	77.2 ± 14.9	75.6 ± 10.5
BMI (kg/m^2)	24.5 ± 4.6	24.3 ± 6.8
Arm strength (lbs)		
1RM lat pull down	83 ± 33	116 ± 39
1RM seated row	61 ± 19	84 ± 31
1RM overhead press	49 ± 30	88 ± 48
1RM biceps curl	22 ± 8	25 ± 14
1RM triceps extension	14 ± 9	24 ± 8

6 Discussion

6.1 Research questions and summary

In this doctoral thesis, the primary goal was to determine factors contributing to perceived exertion in individuals completing exercise, specifically high intensity interval training (HIIT), across a spectrum of health and disease.

The purpose of Chapter 2 was to determine the effect of ratings of perceived exertion (RPE) guided exercise training interventions on cardiorespiratory health and peak power output in individuals with a spinal cord injury (SCI). Using a systematic review and meta-analysis, we examined 9 studies in which they employed at least 2 weeks of RPE-guided exercise training interventions in individuals with an SCI. Despite the heterogeneity in the sample populations and exercise interventions, changes in cardiorespiratory fitness ($\dot{V}O_2$peak) and peak power output favoured post-RPE-guided interventions. A small subset of studies (n=3 for $\dot{V}O_2$peak and n=3 for peak power output) were analyzed using forest plots. Results were in favour of RPE-guided exercise interventions in comparison to non-exercise control. In addition, we found some common characteristics between studies including standardized instructions and familiarization as an important step prior to the use of RPE as an exercise prescription method for exercise interventions in individuals with an SCI. We concluded that RPE-guided exercise interventions are favourable for improvements in $\dot{V}O_2$peak and peak power output in individuals with an SCI.

In Chapter 3, we completed a retrospective analysis to determine the physiological contributors to perceived exertion, measured by leg cycling effort during cardiopulmonary exercise testing (CPET) in non-disabled individuals. While the original RPE scale was closely associated with heart rate responses in young, healthy men that completed a leg cycling exercise test (Borg, 1982), RPE has since been applied in a broad range of exercise settings (Aamot et al., 2014; Antunes et al., 2021). We hypothesized that muscle strength may predict leg cycling effort during a graded exercise test in a large cohort of individuals. In this research we found leg cycling power and maximum power output generated from leg cycling exercise were the strongest predictors of leg cycling effort. Further analysis revealed that the independent physiological predictor of maximum power output was quadriceps strength.

Based on previous recommendations from researchers in the field of SCI, in order to advance the use of RPE in the prescription and monitoring of high intensity interval exercise we first aimed to explore the experiences of individuals with SCI with exercise intensity. Chapter 4 of the thesis explores the foundations of the use of RPE in clinical and community exercise rehabilitation settings. We placed emphasis on the experiences of individuals with lived experience with an SCI, complimented by the experiences of healthcare professionals that support individuals with an SCI during their inpatient and outpatient rehabilitation. Using semi-structured interviews and follow-up interviews after an exercise trial, we found that muscle sensations (i.e., muscle burning, muscle tension, and muscle fatigue) were most mentioned sensation amongst 38 observations for each level of the 0-10 RPE scale. These results were supported by themes and quotes from both individuals with SCI and their healthcare professionals. Chapter 4 helped to drive the development of the post exercise recovery questionnaire and the physiological and psychological variables we considered in Chapter 5 for their association with RPE during arm cycling exercise.

In Chapter 5, we aimed to determine the psychological and physiological variables that contribute to central and peripheral RPE during arm cycling exercise in both non-impaired individuals and individuals who are mobility impaired due to an SCI. Chapter 5 was designed as an acute experimental crossover trial consisting of a maximal graded exercise test on an arm cycling ergometer, followed by RPE-guided high intensity interval training (HIIT) and moderate intensity continuous training (MICT), in a randomized order. During the graded maximal exercise tests, we found that arm strength and age predicted peak central RPE, and the peak feeling scale predicted peripheral RPE in individuals with an SCI. In non-impaired individuals, there were no psychological and physiological variables that contributed to either central or peripheral RPE after a maximal graded exercise test. In the day following RPE-guided MICT and HIIT, both exercise interventions were rated as having high feasibility, high enjoyability, and high recovery overall. Tolerability was slightly higher after RPE-guided MICT individuals with an SCI, whereas there was no difference between exercise conditions in non-impaired individuals.

6.2 Contributions to the existing knowledge

6.2.1 Implementation strategies for ratings of perceived exertion

In the following section considerations for the implementation of perceived exertion, measured by RPE will be outlined. The findings from Chapter 2 and Chapter 4 both support the use of standardized instructions, anchoring, and familiarization as methods to lead to better implementation of RPE and exercise intensity interpretation by study participants and patients with an SCI, alike. Standardized instructions have previously been recommended to introduce participants to the concept, numbers, and descriptors of each level of the RPE scale in use during an exercise trial (Eston & Parfitt, 2007). Due to the similarities between fatigue, pain, and perceived exertion, the verbal instructions may be read aloud for each participant based on a printed script. The instructions include phrases that ask the participant to review the scale, consider a recent time that their perceived exertion was an RPE of 0, described as “nothing at all” on the scale and an RPE of 10, described as “maximum” on the scale, and to describe these instances out loud to ensure that the researcher can verify they are grasping the idea of the scale. Anchoring is a procedure that has been found to improve the reliability of the RPE scale use, whereby the participants are asked to describe the specific sensations or experience associated with each level of the RPE scale (Bok et al., 2022). To elaborate on the previous step, the researcher may ask the participant to think closely about what sensations in their body might arise as they go from a 0 on the RPE scale to 1 on the RPE scale, and each number thereafter up until an RPE of 10. The researcher would slowly go through and prompt the participant to consider different parts of their body, ask what exercise they are imagining, and solidify that sensation as a cue associated with that level for all exercise trials going forward. One study found that self-selected and imposed anchors may lead to different exercise intensity levels, therefore selecting, justifying, and consistently applying the chosen anchors should be based on the study objectives (Malleron et al., 2023). Lastly, a familiarization trial is defined as the process to practice using the RPE scale and associate each level with certain subjective rating of exercise intensity and can be completed in multiple ways, depending on the nature and intensity of the exercise (Green et al., 1999). The familiarization trial may include steps such as standardized instructions and anchoring in one modality of exercise that can be controlled, for example arm cycling on an arm cycle ergometer, and then the secondary trials may be swimming to ensure participants know the arm sensations to aim for at each given RPE level (Green et al., 1999). In Chapter 5, we used a maximal exercise test to familiarize the participants with each level of the scale prior to using RPE to guide the exercise intensity of HIIT and MICT sessions. All techniques are to be implemented ahead of the first trial and are likely to be maintained throughout a trial or a training intervention because it has been documented that RPE familiarity becomes more reliable with use and therefore these processes do not need be completed again within a study.

While cardiorespiratory fitness (CRF) has an inversely proportional relationship with mortality risk, CRF is also closely related to peak power output. Chapter 2 and Chapter 3 together suggest a bidirectional inverse relationship, where RPE-guided training increases peak power output and increases in power are related to higher RPE in clinical populations. Peak power output may be more feasible to measure instead of peak CRF in a clinical setting and our findings indicate that muscle strength is the main determinant of peak power.

6.2.2 Muscle strength as a predictor of ratings of perceived exertion

Subjective measures of exercise intensity, such as the RPE scale, are currently used to prescribe exercise intensity in variety of settings (Faulkner et al., 2008). While the RPE scale has been widely implemented, there are remaining issues associated with the utility of the scale. Our research provides insight on the clinical application of RPE in a non-disabled population (Chapter 3), the perceptions of individuals with an SCI and healthcare professionals (Chapter 4 and 5), and lastly experimental data on central and arm RPE arm cycling exercise (Chapter 5). In its totality, this research contributes to an understanding of the physiological underpinnings of perceived exertion during exercise as measured by the RPE scale. Throughout the thesis, we examine physiological and psychological variables that contribute to RPE. We found novel variables, and specifically alternatives to heart rate, that were associated with and predicted RPE. This finding that variables such as muscle strength, but not heart rate, were predictive of RPE is unsurprising given the non-linear relationship between workload and heart rate in clinical populations, however we believe that these findings may be transferrable to non-disabled populations. The findings in Chapters 3, 4 and 5 suggest that muscle strength and power are strongly related to RPE, albeit in different types of exercise modalities, muscle groups, and types of RPE, based on the abilities of the population. Both qualitative and quantitative data collection methods support the hypothesis that RPE during exercise is related to power and muscle strength.

6.2.3 Recovery after ratings of perceived exertion-guided exercise training

In this doctoral thesis, we found RPE-guided MICT and HIIT were tolerable, feasible, and enjoyable when assessed in the day following the exercise session. To measure these responses, we developed a post exercise recovery questionnaire that can be used in the days following exercise training. Based on the results in our post exercise questionnaire, we concluded that RPE-guided HIIT protocol, designed by Graham and colleagues, may be best suited for individuals with an SCI that are new to HIIT (Graham et al., 2019).

6.3 Limitations and considerations

6.3.1 Study design and methodological controls

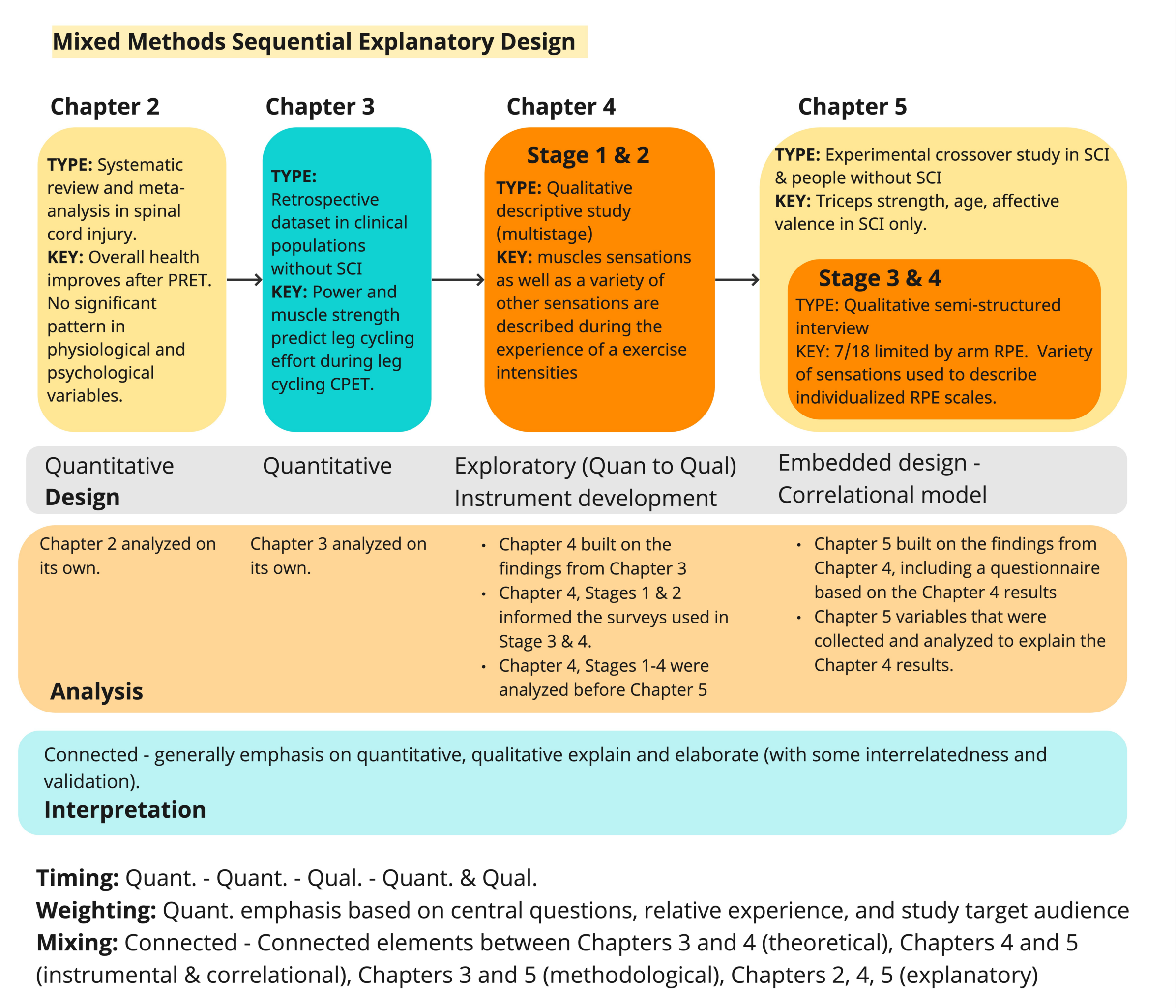
The chapters of this doctoral thesis are not without limitations. Given the well-documented benefits of exercise training, it is important to acknowledge the comparison was pre-exercise training or non-exercise control. There is lack of literature on comparing the type of exercise prescription methods and therefore, we were unable to compare to prescription by heart rate, percentage of peak oxygen uptake (%$\dot{V}O_2$peak), or other methods. We hypothesize that individuals prescribed exercise using RPE-guided methods may have a higher variability in their exercise intensity when completing exercise in an unsupervised setting. However, RPE may lead to longer term adherence to exercise habits because choosing one’s own exercise workload based on a subjective ratings of exercise intensity appeal to an individual’s autonomy and mastery as part of self-determination theory (Teixeira et al., 2012).

6.3.2 Clinical populations

Recruitment to participate in research studies of individuals with an SCI is challenging. There are many psychological and physical barriers associated with wheelchair users and specifically individuals with a traumatic SCI prior to engaging in the exercise itself (Kehn & Kroll, 2009). The participants recruited in this doctoral thesis are individuals that had the willingness to meet a combination of research requirements, including but not limited to travel costs and organization, psychological barriers associated with unfamiliar research environments, and the financial and time capacity that allows any individual to take part in the research. Given that each level and completeness of injury cause a unique combination of sensory and motor function changes, the SCI population is heterogenous. Recruitment for Chapters 3, 4, and 5 occurred in Hamilton, Ontario and therefore the research findings may be unique to the population and the clinical practices in the region. The objectives of this doctoral thesis were to understand the variables that contribute to perceived exertion measured by RPE, particularly during high intensity interval exercise and that translate to an applied setting. Research in a translational context can be challenging because there is lack of control compared to a traditional laboratory setting. Wherever possible we included participant feedback, member checking, and consultation with clinicians and healthcare practitioners that work in the area of rehabilitation for individuals with an SCI.

6.3.3 Challenges associated with mixed methods research

There are many challenges associated with cross disciplinary research, such as varying definitions of perceived exertion (Halperin & Emanuel, 2020). Different research methodologies and approaches can result in different conclusions so each chapter must be interpreted within the context that the data was collected. Taken together, this doctoral research employed a mixed methods sequential explanatory design (see Figure 1), whereby we undertook quantitative and qualitative studies in sequence and we sought to explain the quantitative results with qualitative results and context (explanatory; Creswell et al. 2007). While muscle sensations were most used to describe exercise intensity in individual with an SCI and their healthcare professionals (Chapter 4, a qualitative descriptive study), frequentist methods are not often employed in qualitative papers (Leppink, 2017). Additional steps were taken throughout to consider the opinions of members within the SCI community. The findings of our work have been considered in the context that they were collected and for the purpose of application in clinical and community exercise settings.



Mixed Methods Sequential Explanatory Design

Chapter 2

TYPE: Systematic review and meta-analysis in spinal cord injury.
KEY: Overall health improves after PRET. No significant pattern in physiological and psychological variables.

Chapter 3

TYPE: Retrospective dataset in clinical populations without SCI
KEY: Power and muscle strength predict leg cycling effort during leg cycling CPET.

Chapter 4

Stage 1 & 2
TYPE: Qualitative descriptive study (multistage)
KEY: muscles sensations as well as a variety of other sensations are described during the experience of a exercise intensities

Chapter 5

TYPE: Experimental crossover study in SCI & people without SCI
KEY: Triceps strength, age, affective valence in SCI only.

Stage 3 & 4
TYPE: Qualitative semi-structured interview
KEY: 7/18 limited by arm RPE. Variety of sensations used to describe individualized RPE scales.

Design
Quantitative
Quantitative
Exploratory (Quan to Qual) Instrument development
Embedded design - Correlational model

Analysis
Chapter 2 analyzed on its own.
Chapter 3 analyzed on its own.
- Chapter 4 built on the findings from Chapter 3
- Chapter 4, Stages 1 & 2 informed the surveys used in Stage 3 & 4.
- Chapter 4, Stages 1-4 were analyzed before Chapter 5
- Chapter 5 built on the findings from Chapter 4, including a questionnaire based on the Chapter 4 results
- Chapter 5 variables that were collected and analyzed to explain the Chapter 4 results.

Interpretation
Connected - generally emphasis on quantitative, qualitative explain and elaborate (with some interrelatedness and validation).

Timing: Quant. - Quant. - Qual. - Quant. & Qual.
Weighting: Quant. emphasis based on central questions, relative experience, and study target audience
Mixing: Connected - Connected elements between Chapters 3 and 4 (theoretical), Chapters 4 and 5 (instrumental & correlational), Chapters 3 and 5 (methodological), Chapters 2, 4, 5 (explanatory)

Figure 1. Diagram depicting the design, analysis, and interpretation (top to bottom) of Chapters 2 to 5 (left to right). Summary of the diagram is listed at the bottom, including

the timing, weighting, and mixing. Each of the described components contribute to the overall decision for naming the doctoral thesis as “mixed methods sequential explanatory design” based on Creswell et al. 2007. Note. Quant. = Quantitative; Qual. = Qualitative.

6.4 Recommendations for future work

6.4.1 Neurophysiological basis of ratings of perceived exertion

This thesis determined the qualitative and quantitative variables that contribute to central RPE (i.e., breathing, chest) and peripheral RPE (i.e., leg, arm), however the processes that integrate sensations and determine how individuals choose an RPE at the level of the brain have not been explored. Interoception is the process that enables individuals to sense the signals in their body, such as heart rate, temperature, hunger and thirst (Craig, 2002). Previous research has shown that individuals with type 1 diabetes with higher levels of mindfulness have better interoceptive awareness of their glucose levels (Schultz, 2020). In other words, they know that their body is in a hypo- or hyperglycemic state, without a monitor. Functional magnetic resonance imaging (fMRI) studies in non-disabled individuals have suggested that brain regions communicate and cooperate to a larger degree as the physical force exertion level increases during isometric arm exercise (Ismail et al., 2022). The concept of interoception may explain the higher number of observations for an RPE of 10 in individuals with an SCI found in Chapter 4. However, studies within individuals with an SCI should be conducted to explain the similarities and differences between individuals of different abilities and modalities of exercise training.

6.4.2 Spinal cord injury specific ratings of perceived exertion scale and future exercise guidelines for individuals with a spinal cord injury

It is the responsibility of researchers that develop the guidelines, health care professionals that implement them, and policy makers that communicate them to use words and campaigns that resonate with a broader audience. One potential advance is to change the way we describe exercise intensity (Hutchinson & Goosey-Tolfrey, 2021). Based on the findings in this doctoral work, we recommend a new iteration of the RPE scale that can broadly be used for individuals with an SCI and the broader population based on the following three adaptations: 1) reduce the number of levels from 10 levels to 5 levels, representing levels 0, 3, 5, 7, 10 on the current 0-10 RPE scale, 2) remove the word “severe” as a one-word descriptor, and 3) build in muscle sensation descriptions alongside each level.

There are many studies that have examined the use of HIIT and strength training for individuals with an SCI (Astorino et al., 2021; Peters et al., 2021; Santos et al., 2022). Chapter 5 of this thesis uses an RPE-guided protocol that is suitable for individuals with an SCI that have little prior experience with HIIT. We recommend that the future SCI guidelines include guidelines that are separate for moderate and vigorous intensity exercise training scaled to the time commitment recommended for each intensity. SCI-specific HIIT should be prescribed using subjective ratings of exercise intensity and include sensation descriptions or pictograms to eliminate the need for instructions, similar to work done on the ratings of fatigue scale (Micklewright et al., 2017). There are currently no intensity recommendations associated with the strength training guidelines for individuals with an SCI. RPE has been used as a method for exercise intensity strength training prescription and monitoring in non-disabled individuals and RPE-based loading may even have a small strength advantage over percentage of 1 repetition maximum (%1RM) loading methods (Helms et al., 2018). Chapter 5 shows how individuals with an SCI that have greater triceps strength have lower RPE during a maximal exercise test and these findings may translate to lower RPE during activities of daily living. While many people with an SCI currently engage in strength training, the intensity at which to complete training for health benefits is not currently included in the SCI-specific guidelines.

6.4.3 Development of an accessible method for maximal exercise testing

While previous models of use of RPE for prescribing and monitoring exercise in individuals with SCI have been described, there has yet to be an accessible protocol to determine aerobic capacity in individuals with an SCI. In contrast there are a variety of submaximal predictive protocols that can be used to determine maximal CRF in non-disabled individuals and many of these protocols do not require laboratory grade equipment (Agarwala & Salzman, 2020; Bohannon & Crouch, 2019; Nakagaichi & Tanaka, 1998; Shephard et al., 1976). One example of these predictive and feasible tests is the modified Canadian Aerobic Fitness Test (mCAFT), originally called the Canadian Home Fitness Test, which can be used to predict $\dot{V}O_2$peak using an audio track and two-steps as well as anthropometric assessments (Shephard et al., 1976). This test has been validated to be completed by a kinesiologist or in a remote community exercise setting that does not have access to a metabolic cart technology (Weller et al., 1995). Based on the current research, a combination of 1-RM arm strength testing, age, and RPE during exercise may be an effective combination for predicting aerobic capacity in individuals with an SCI in rehabilitation or in the community. The development of a protocol would be valuable for healthcare professional that serve individuals with an SCI that live in remote or under resourced settings to determine the intensity to complete daily exercise training for health benefits.

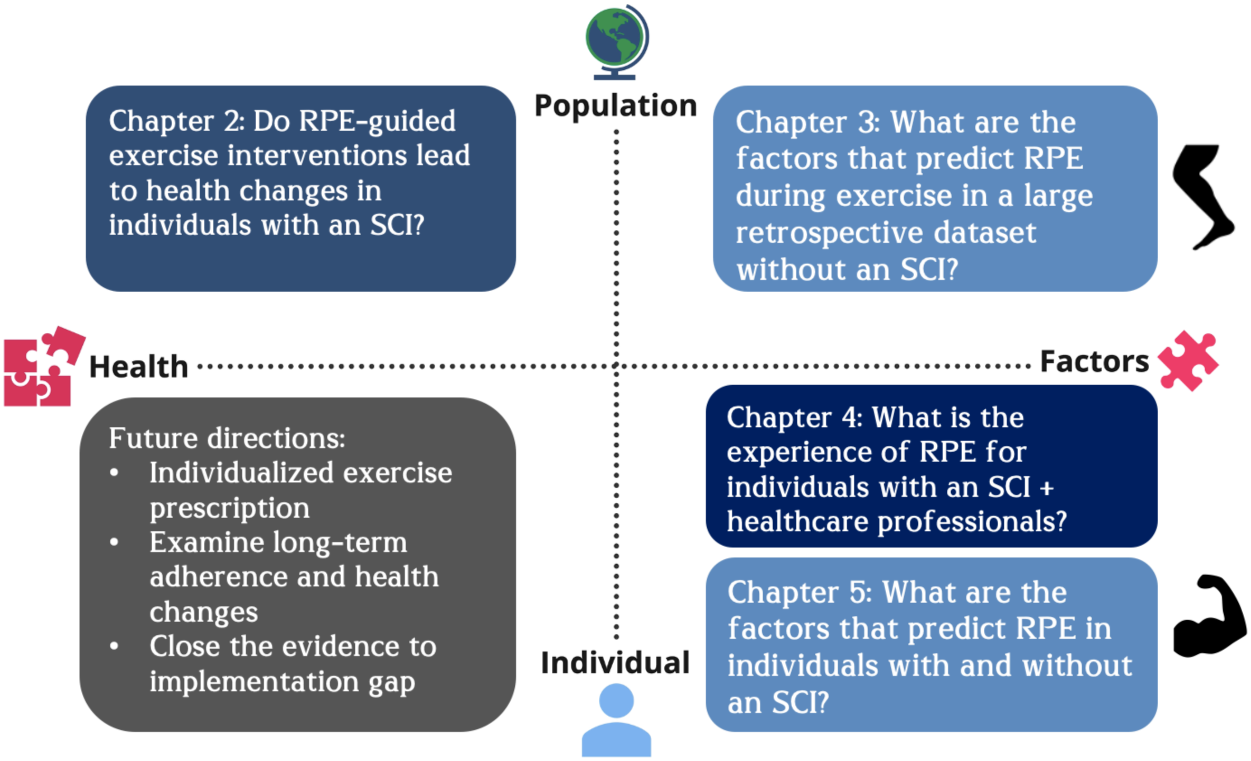


Figure 2. All four study chapters can be placed on this XY graph including health and factors on the x-axis and individual to population on the y axis. Chapter 5 mirrors the study design of Chapter 3, except with a focus on the upper body and in a smaller cohort of individuals with and without an SCI. Future directions are summarized in the bottom left quadrant.

6.5 Key takeaways

The main findings of this research can be summarized into the following new and noteworthy takeaways:

- Exercise training interventions in which the exercise intensity is prescribed by RPE can lead to changes in peak power output and CRF, measured by $\dot{V}O_2$peak, in individuals with an SCI.
- Leg cycling power and leg strength are predictive of leg cycling effort in non-disabled individuals referred for graded exercise testing.
- Muscle sensations are the most reported perceptions during past and present experiences during exercise in individuals with an SCI and their healthcare professionals, especially when describing high intensity exercise.
- Arm strength and age are predictive of central RPE and the feeling scale is predictive of arm RPE in individuals with an SCI during maximal graded arm cycling exercise.
- Both participants with, and without, an SCI reported ratings of high tolerability, feasibility, and enjoyability one day after RPE-guided HIIT and MICT on an arm cycle ergometer. Tolerability was more positive for MICT compared to HIIT in individuals with an SCI.

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