CARDIAC FUNCTION AND PHYSICAL ACTIVITY PARTICIPATION

IN INDIVIDUALS WITH SPINAL CORD INJURY

by

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B.Kin., The University of British Columbia, 2015

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Kinesiology)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2017

Abstract

Individuals with spinal cord injury (SCI) are at greatly increased risk of cardiovascular disease (CVD). This is likely due to physical inactivity and impaired sympathetic control of the heart and blood vessels, resulting in cardiovascular dysfunction. Cardiovascular dysfunction in individuals with SCI is associated with injury level, whereby individuals with higher lesions exhibit greater dysfunction. In people without SCI, cardiac dysfunction predicts CVD. The studies that have investigated cardiac indices in individuals with SCI tend to agree that cardiac atrophy and impaired systolic function occur following SCI. Physical activity is a key method to decrease CVD risk and improve cardiac function, yet few studies have examined the relationship between cardiac function and physical activity in individuals with SCI. Those that have investigated this relationship have used subjective measures of physical activity. The current guidelines for physical activity participation for individuals with SCI were based on a systematic review of the evidence on the benefits of physical activity, yet there was inadequate evidence to prescribe activity intensity and duration to improve cardiovascular health in this population. Individuals with SCI also experience numerous barriers and facilitators to physical activity participation that affect their ability to meet the guideline recommendations. The objectives of this thesis, therefore, were: 1) to objectively measure physical activity in individuals with SCI, using wrist-worn accelerometry during a six-day physical activity monitoring period, and to evaluate the utility of group based wrist accelerometry cut-points to estimate physical activity intensity by comparing MVPA determined by individual cut-points to MVPA determined by group-based cut-points; 2) to determine the relationship between objectively measured physical activity and cardiac structure and function in individuals with SCI across a range of injury levels, and 3) to

explore the barriers and facilitators to physical activity participation experienced by individuals with SCI during a six-day physical activity monitoring period.

Preface

All data contained in this thesis were collected by Laura McCracken at the West Lab within the School of Kinesiology and the International Collaboration On Repair Discoveries (ICORD). Methodologies were reviewed and approved by both the UBC Clinical Research Ethics Board (Effects of physical activity and sympathetic cardiac regulation on cardiac function in individuals with chronic spinal cord injury, H15-00852), and the Vancouver Coastal Health Research Institute. A version of chapter 2 of this thesis was submitted for publication and was under review at *Archives of Physical Medicine and Rehabilitation* at the time of thesis submission.

I was the lead investigator on the project, responsible for concept development, data collection and analysis, and manuscript composition. Jasmin Ma and Gevorg Egingyan were involved in data collection. Dr. Andrea Bundon was involved in concept development. Dr. William Sheel was part of the supervisory committee and was involved in concept development. Dr. Laura Hurd Clarke was part of the supervisory committee and was involved in concept development, data analyses and thesis revisions.

Dr. Christopher R West was the supervisory author on the project and was involved in concept formation, data collection and thesis revisions.

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List of abbreviations

- **ASIA:** American Spinal Injury Association
- **BMI:** Body Mass Index
- **CPM:** Counts Per Minute
- **CRP:** C-reactive protein
- **CVD:** Cardiovascular Disease
- **E/A:** Ratio of early to late transmitral filling velocities during diastole
- **EDV:** End Diastolic Volume
- **EF:** Ejection Fraction
- **ESV:** End Systolic Volume
- **HDL:** High-density Lipoprotein
- **HR:** Heart Rate
- **ICORD:** International Collaboration on Repair Discoveries
- **LDL:** Low-density Lipoprotein
- **LTPA:** Leisure Time Physical Activity
- **MET:** Metabolic Equivalent
- **MVPA:** Moderate-to-Vigorous Physical Activity
- **PADS:** Physical Activity and Disability Scale
- **PARA-SCI:** Physical Activity Recall Assessment for people with SCI
- **PASIPD:** Physical Activity Scale for Individuals with Physical Disabilities
- **Q:** Cardiac Output
- **SCI:** Spinal Cord Injury

- **SV:** Stroke Volume
- **VM:** Vector Magnitude
- **VMCPM:** Vector Magnitude Counts per Minute

Acknowledgements

I would like to express my appreciation and thanks to my supervisor Dr. Christopher West for his exceptional support and guidance. Without his patience and encouragement this thesis would not have been possible. I would also like to thank my committee members, Dr. Laura Hurd Clarke and Dr. William Sheel, for their invaluable insight and contributions.

I would like to thank the members of the West Lab who have supported and guided me through my thesis work, as well as Franco Chan, Jasmin Ma, Dr. Andrea Bundon, Dr. Christine Voss and Dr. Kathleen Martin Ginis. I would like to thank Jordan Squair for his patience and support. I also thank ICORD, the University of British Columbia and the Canadian Institutes of Health Research for their financial support during this thesis.

Lastly, I would like to thank my family, who have supported me through years of education both morally and financially.

Dedication

To my family.

Chapter 1: Literature review

1.1 Cardiovascular consequences of SCI

Overview

Spinal cord injury (SCI) results in not only motor and sensory impairment, but also sympathetic nervous system damage that may lead to cardiovascular dysfunction.[1] Specifically, loss of supraspinal control of the sympathetic nervous system as well as low sympathetic activity below the level of injury occur following SCI.[1] This dysfunction is related to the neurological level of injury, whereby higher injury levels tend to be associated with greater cardiovascular dysfunction.[2] With reference to the heart, this is likely because individuals with an autonomic complete injury above the T1 spinal level do not have supraspinal sympathetic control of the heart and vasculature, while individuals with a T1-T5 lesion have partial-to-full cardiac sympathetic control, and individuals with an injury below T5 have complete cardiac sympathetic control.[3] It is thought that the decentralization of the sympathetic nervous system is a significant contributor to cardiovascular disease (CVD). In fact, people with SCI are at greatly increased odds of cardiovascular disease,[4] and the risk of CVD has also been found to be associated with both the level and severity of SCI.[5] In a study of 545 individuals with SCI, individuals with tetraplegia had a 16% greater risk of CVD than individuals with paraplegia, and individuals with a complete SCI had a 44% greater risk of CVD than those with incomplete injuries.[5] Cardiovascular disease risk factors that are higher in individuals with SCI include dyslipidemia, chronic inflammation, blood pressure irregularities and abnormal glycemic control.[4]

1.2 Cardiovascular disease risk factors in individuals with SCI

Dyslipidemia

Abnormal lipid values are well established risk factors for CVD and diabetes development.[6] High total cholesterol, high low-density lipoprotein (LDL), and low high-density lipoprotein cholesterol (HDL) occur more frequently in individuals with SCI when compared to age and sex matched controls.[7] Individuals with tetraplegia exhibit greater dyslipidemia than those with paraplegia,[8] and time since injury has been found to be a stronger predictor of dyslipidemia than diet.[9] This suggests that metabolic changes and inactivity secondary to SCI have significant impacts on dyslipidemia in these individuals.[10]

C-reactive protein

Inflammation plays an important role in the development of CVD. C-reactive protein (CRP), which is secreted by the liver during inflammation and is a commonly used measure of inflammation, is an independent and non-traditional risk factor for CVD in the non SCI population.[11] C-reactive protein may have a direct role in atherosclerosis, thrombosis, and plaque rupture.[11] Elevated C-reactive protein has been found in individuals with SCI compared with age and race matched non-SCI controls.[12] There is mixed evidence on the association between CRP levels and injury level; Liang and colleagues (2008) were unable to make conclusions about this relationship[12,13] while Gibson and colleagues (2008) found a significant independent association between level of lesion and CRP levels, whereby CRP values were 74% higher in individuals with tetraplegia versus individuals with paraplegia.[14]

Body composition

Daily energy expenditure decreases following SCI by about 10-50% and is dependent on the muscle mass that has lost central control.[15,16] Consequently, fat mass increases and obesity is more prevalent in individuals with SCI, and is a key CVD risk factor in this population.[17] Increased mortality risk in SCI may be partly due to changes in body composition specific to this population.[18] Body composition measures are needed in order to classify an individual as normal weight, being overweight or obese, but as this can be expensive and difficult, the body mass index (BMI) is commonly used.[16] Previous work has found that standard BMI classification of obesity is inaccurate for individuals with SCI, who may have up to 15% more fat mass than BMI-matched non-SCI control subjects.[19] Thus, a decrease in the BMI cut-off for obesity from 30 to 25kg/m^2 has been suggested for individuals with SCI.[20] As such, other measures to estimate body fat percentage and classify risk may be more appropriate for this population.[17] Although there is no current consensus on the best clinical measure of obesity in the SCI population, abdominal obesity, specifically visceral adipose tissue, is an independent risk factor for coronary heart disease in non-SCI populations.[18] Higher visceral adipose tissue, total adipose tissue and the ratio of visceral adipose tissue to subcutaneous adipose tissue have been found in individuals with SCI compared to non SCI individuals matched for age, sex, and waist circumference.[18] After adjusting for BMI and age, Edwards and colleagues (2008) found that individuals with SCI had more than twice the amount of visceral adipose tissue per centimeter of waist circumference, likely attributable to abdominal muscle atrophy and increases in proportion of fat to fat free mass.[18]

Diabetes and insulin sensitivity

Individuals with diabetes are at an increased risk of CVD,[21] and so are individuals with SCI.[22] However, the combined effects of type II diabetes and SCI on CVD risk are unknown. The increased adiposity following SCI has been associated with metabolic sequelae such as glucose intolerance, insulin resistance and hyperlipidemia.[23] Specifically, studies have suggested that increased prevalence of insulin resistance and glucose intolerance in people with SCI are secondary to changes in body composition including skeletal muscle loss and increased intramuscular fat levels.[24,25] Put together, these factors place individuals with SCI at two-fold increased odds of type II diabetes, independent of other known risk factors.[22]

1.3 Cardiac consequences of SCI

1.3.1 Rationale for studying cardiac structure and function following SCI

Cardiac dysfunctions are associated with an increased risk of CVD in people without SCI.[26] In individuals with SCI, multiple mechanisms may lead to cardiac changes, including the loss of supraspinal control of sympathetic input to the heart and vasculature,[27] reduced sympathetic activity below the injury level,[28] morphological changes of sympathetic neurons,[29] peripheral alpha-adrenoreceptor hypersensitivity,[30] cardiac beta-receptor hypersensitivity,[31] autonomic dysreflexia,[32] reduction in venous return,[33] and physical inactivity.[34] The loss of sympatho-excitatory control to the heart may impair the ability to increase heart rate and contractility, and the loss of supraspinal input to blood vessels may result in venous pooling and subsequent reductions in venous return and preload in the heart. Specifically, altered vascular tone,[35] reduction in blood volume,[36] decreased skeletal muscle pump[37] and respiratory pump activity following SCI [38] may contribute to the reduced venous return seen in individuals with SCI.[39] This reduction in venous return depends on injury level and completeness, as the sympathetic input to the upper body vasculature arises from the T1-T5 level of the spinal cord whilst the input to the lower body and abdominal region arises from the T6-T12 levels.[40] Following SCI, individuals with tetraplegia and high paraplegia with injuries at T5 and above exhibit the most cardiovascular dysfunction.[1,41]

1.3.2 Cardiac changes following SCI: Structure

The studies that have investigated the cardiac consequences of SCI have used echocardiography to measure cardiac structure and function. The lesion level dependency of alterations in cardiac structure has been examined, and the evidence suggests that the left ventricle is smaller in individuals with tetraplegia, while the evidence is unclear for individuals with paraplegia. Kessler and colleagues (1986) found a 26% decrease in left ventricular mass index, a measure of left ventricular mass relative to body surface area, in individuals with tetraplegia compared to both non-SCI individuals and individuals with paraplegia. The internal diameter of the left ventricle and the diameter of the left atrium were also lower in individuals with tetraplegia.[42] These findings of cardiac atrophy in individuals with tetraplegia have been confirmed by subsequent studies,[33,43] but the evidence is less conclusive for individuals with paraplegia. Studies investigating cardiac consequences of paraplegia have used both pooled samples of individuals with paraplegia and tetraplegia, as well as just individuals with paraplegia. There are conflicting findings among studies with pooled samples, as some reported cardiac atrophy following SCI[44] while others do not.[45,46] Similarly, findings are conflicting in studies with samples of only individuals with paraplegia. Huonker and colleagues (1998) found left ventricular mass index and left ventricular internal diameter during diastole were lower in sedentary individuals with paraplegia compared to individuals without SCI, while wall thickness was no different. Maggioni and colleagues (2012), however, found lower end diastolic diameter in individuals with paraplegia, but similar left ventricular mass indices, and slightly higher wall thickness in individuals paraplegia.[47] Cross-sectional studies comparing active and inactive individuals with SCI reveal that physical activity may attenuate or prevent structural cardiac changes following SCI in individuals with paraplegia, however there is some conflicting evidence. Washburn and colleagues (1986) found that LV mass index was significantly positively correlated with self-reported physical activity levels in a pooled sample of individuals with tetraplegia and paraplegia. Studies of cardiac structure in individuals with paraplegia have found that athletic people have larger LV mass index,[45,47] higher heart volume relative to body weight,[48,49] and larger LV diameters,[45,49] as well as lower relative wall thickness [45] compared to inactive individuals with paraplegia. Similar structural parameters have been found in athletic individuals with paraplegia compared to sedentary and active people without SCI.[45,49,50]

In contrast, other studies have found no difference in structural indices between active and sedentary individuals with SCI.[51,52] Gates and colleagues (2002) found no differences in any structural indices in a comparison of individuals with paraplegia who were either endurance trained, power-trained or sedentary.[51] Schumacher (2009) also found similar left ventricular diameters and heart volumes relative to body weight in their study of active and sedentary individuals with tetraplegia and paraplegia.

1.3.3 Cardiac changes following SCI: Systolic function

Systolic measures provide information about the function of the heart during contraction, while diastolic measures provide information about cardiac relaxation. Kessler and colleagues (1986) found markedly lower resting stroke volume and cardiac output in individuals with tetraplegia, but not paraplegia, compared to individuals without SCI. West and colleagues (2012) also found impaired resting systolic function in highly trained athletes with tetraplegia compared to individuals without SCI. They found lower left ventricular ejection fraction, cardiac output and stroke volume in the tetraplegia group[53]. In contrast, De Groot and colleagues (2006) found that global systolic function was not impaired in individuals with tetraplegia, although there was a trend toward decreased cardiac output[33]. Driussi and colleagues (2014) compared measures of systolic function in a group of individuals with tetraplegia or paraplegia to individuals without SCI, and also found no difference in stroke volume or ejection fraction between groups. They found that cardiac output and cardiac output indexed to body surface area were lower in participants with SCI. Systolic myocardial contraction velocity, a measure of left ventricular contractility less dependent on preload, was higher in the participants with SCI. The ratio of peak systolic pressure to end diastolic volume, an afterload corrected measure of left ventricular systolic function, was also higher in the SCI group. The authors propose that this reflects an increase in left ventricular function to compensate for decreased venous return and impaired ability to increase heart rate.[54] Currie et al (2016) compared cardiac function between Paralympic athletes with paraplegia and tetraplegia and found reduced stroke volume and cardiac output in the tetraplegia group.[55] They also measured indices of left ventricular mechanics, including strain, strain rate, rotation, rotation rate and twist and untwisting rates. They found that despite the reduction in global systolic function seen in the individuals with tetraplegia, systolic left ventricular mechanics were maintained in this group, yet reduced in the paraplegia group. The authors suggest that the increase in systolic mechanics in the tetraplegia group may be attributable to reduced afterload, and the decrease in mechanics in the paraplegia group may not be pathological but rather could be indicative of a resetting of left ventricular mechanics to lower resting values in response to high training volumes.[55] In a comparison of sedentary individuals with tetraplegia and paraplegia to active individuals with SCI and able bodied controls, De Rossi and colleagues (2013) found similar left ventricular mass in all groups, but lower left ventricle diameter and stroke volume in the sedentary SCI group.[45] When the SCI group was divided by injury level, there was no difference in systolic function between active and sedentary individuals with tetraplegia. Within the paraplegia group, however, the active group had higher stroke volume, but there was no difference in ejection fraction.[45] Huonker and colleagues (1998) also found lower stroke volume in sedentary individuals with paraplegia compared to active individuals with paraplegia and able-bodied individuals, however there were no differences in ejection fraction. In contrast, other studies have found similar resting systolic function in active and sedentary individuals with paraplegia.[47,51] Gates and colleagues (2002) found no differences in stroke volume and ejection fraction between individuals with paraplegia who were either endurance trained, power-trained or sedentary.

1.3.4 Cardiac changes following SCI: Diastolic function

There are mixed findings on diastolic function in SCI. Some studies report no difference in the ratio of early to late filing (E/A) between individuals without SCI and individuals with tetraplegia,[33,43] individuals with paraplegia,[47] and pooled samples of individuals with tetraplegia and paraplegia.[45,46] Other studies have found diastolic dysfunction in pooled samples of individuals with tetraplegia and paraplegia. Specifically, studies have reported decreased early transmitral filling velocity (E),[54] tissue velocity (E'),[45,46,54] ratio of early to late filling velocity (E/A),[54] ratio of early to late myocardial tissue velocities during diastole (E'/A'), and higher ratios of early transmitral to myocardial tissue velocities (E/E').[45,46,54] Increased isovolumetric relaxation time has also been found in individuals with paraplegia.[47] Maggioni and colleagues (2012) also found no differences in isovolumetric relaxation time, filling velocities, or tissue velocities between active and inactive individuals with paraplegia. Gates and colleagues (2002) found that late left ventricular transmitral filling velocity (A) was lower and consequently E/A was higher in sedentary individuals with paraplegia compared to endurance-trained individuals with paraplegia. The authors explain that this may suggest lower left ventricular compliance in the endurance trained individuals, but should be interpreted with caution given the small sample size and heterogeneous E/A ratios in the sedentary group.[51] Price et al. (2000) found no difference in filling velocities in a comparison of wheelchair athletes with paraplegia, long distance runners and sedentary control participants without SCI, however, the paraplegic group consisted of two individuals who did not have SCI.[50] In a comparison of highly trained athletes with tetraplegia to recreationally active individuals without SCI, West et al (2012) also found no differences in filling velocities. De Rossi (2013) found that athletes with tetraplegia had lower E/E' and higher E' compared to sedentary individuals with tetraplegia, while athletes with paraplegia demonstrated higher E'/A' compared to sedentary paraplegic individuals.

1.3.5 Exercise training and cardiac indices following SCI

There is convincing preclinical evidence that passive lower limb exercise can partially reverse cardiac dysfunction following SCI.[56] Few studies have used echocardiography in longitudinal studies investigating cardiac responses to exercise training in individuals with SCI, however, and the findings are mixed. Arm crank ergometry is a common exercise method for individuals with SCI, however, a 16 week training program was found to have no effect on resting cardiac structure or function in a group of 9 individuals with paraplegia.[57] Turiel et al. (2010) found improvements in systolic and diastolic function following a six-week robotic assisted treadmill-training program in 14 individuals with SCI, 8 of which had traumatic SCI. They found that ejection fraction increased, isovolumetric relaxation time decreased, late transmitral filling velocity decreased, E/A ratio increased, and the thickness of the interventricular septum increased.[58] However, they found no increases in chamber diameters. Nash et al (1991) found that left ventricular mass, diameters and wall thickness were increased in a group of eight individuals with tetraplegia following six months of functional electrical stimulation cycling. They concluded that cardiac atrophy following SCI was reversed with this method of training, attributable to pressure and volume overload of the heart.[59] Gibbons (2016) found improved cardiac structure and function in five individuals with SCI following an 8-week FES rowing training intervention. Structural improvements included increased left ventricular internal diameter during diastole, left ventricular volumes and left ventricular mass, and decreased relative wall thickness. Global systolic function improved as indicated by increased stroke volume, ejection fraction, and cardiac output. Markers of diastolic function improved, with increased early transmitral filing velocity, E/A, E', E'/A', and flow propagation velocity, as well as decreased A, A', and E/E'. While the results of this study are favourable, the small sample size and high variability in participant characteristics prevents the authors from making conclusions about the effects of FES training on the heart.[60] Overall, the wide range of training program modalities, duration and participant characteristics is likely responsible for discrepancies seen in training effects. Additional research is needed describing the effects of exercise training on the heart in individuals with SCI.

1.4 Physical activity and cardiovascular health following SCI

Self reported physical activity has been associated with a decrease in cardiovascular disease risk in SCI.[12,61,62] Higher physical activity levels in individuals with SCI have been associated with lower fasting glucose levels, decreased abdominal obesity, lower triglycerides, inflammation and higher HDL. Liang and colleagues (2008) measured physical activity levels in 131 men with chronic SCI using the Physical Activity Scale for Individuals with Physical Disabilities (PASIPD). They divided participants into tertiles based on physical activity levels and found that the high physical activity tertile was associated with significantly lower odds for elevated triglycerides, high CRP and metabolic syndrome. While the PASIPD has been validated in individuals with disabilities, the authors assigned standardized non-SCI MET values to physical activities reported by individuals with tetraplegia and paraplegia, which may misrepresent activity intensity.[13]

Manns and colleagues (2005) assessed self-reported physical activity and various cardiovascular disease risk factors in 22 men with chronic paraplegia. They found that lower self-reported physical activity levels as assessed by the Physical Activity and Disability Scale (PADS), were associated with higher fasting glucose, lower HDL levels and larger abdominal sagittal diameter.[61] The PADS, however, was not validated for use in SCI. In another study of individuals with paraplegia, Mojtahedi and colleagues (2008) found that insulin sensitivity was higher in highly active male and female athletes with chronic paraplegia than it was in BMI and age matched sedentary control participants without SCI.[63] In a study of 75 men and women with chronic traumatic SCI, Buchholz et al (2009) examined self-reported leisure time physical activity (LTPA) using the PARA SCI and measured various cardiovascular disease risk factors. Active participants who engaged in at least 25 minutes a day of mild to moderate intensity LTPA had significantly lower BMI, percent fat mass, CRP, insulin resistance and higher percent fat free mass than inactive participants.[62] While several studies have investigated the relationship between subjective and recall based physical activity measures and CVD risk factors, none have used objective measures, which may preclude an accurate determination of how physical activity impacts CVD risk factors in SCI.

1.5 Barriers and facilitators to physical activity participation in individuals with SCI

Physical activity may be important for cardiovascular health in individuals with SCI. There are, however, numerous unique barriers and facilitators for physical activity participation in this population. These factors have been identified through studies of individuals with SCI, professionals who work with people with SCI, or in the fitness and recreation industry as well as facilities for physical activity participation and designers of these facilities. The research in this area has been both quantitative and qualitative in nature and has included a range of methods, such as surveys, questionnaires, focus groups and interviews. Some studies included a measure of each participant's activity level based on self-report, while others did not. It is clear from the literature that the barriers and facilitators to physical activity participation are interacting and complex. For example, Rimmer (2004) identified ten categories of barriers and facilitators for physical activity participation among persons with disabilities based on focus groups completed in ten regions across the United States with consumers with disabilities, architects, fitness and recreation professionals, city planners and park district managers. These categories included the physical environment, economic and other resources, equipment, knowledge, education and information, and emotional and psychological barriers.[64] The authors concluded that accessibility is a very complex issue and that perceptions of accessibility, specifically whether or not a facility is accessible, could possibly be quite different between individuals with disabilities and professionals who work with them.[64]

The factors limiting exercise participation have been proposed to include barriers related to the individual and their environment. Scelza and colleagues (2005) surveyed 72 individuals with SCI (aged 19-80, 50 males and 22 females) using a comprehensive survey including 34 items asking about the availability of exercise facilities and various resources and concerns about barriers possibly limiting exercise participation. These items were followed by five open-ended questions that elaborated on issues limiting participation.[65] The authors identified three areas that encompassed the most frequently cited barriers to exercise, namely: 1) intrapersonal barriers such as lack of motivation or interest, 2) lack of resources including those related to economic factors and limited knowledge, and 3) structural or architectural barriers, for example facility accessibility.[65] Seventy-four percent of participants reported interest in an exercise program while only 45.8% participated in one.

Factors impacting physical activity participation also include factors related to the individual and their social and physical environments. Levins and colleagues (2004) conducted semi structured, in depth interviews with eight individuals with SCI (five males and three females aged 24-59) in order to investigate individual and societal influences on physical activity participation.[66] The researchers encouraged a broad conceptualization of physical activity in order to acknowledge the wide range of potential benefits of any physical activity and allow for greater latitude in discussion during the interviews. Current and pre-injury physical activity levels were reported in terms of a list of activities participants were involved in, with little indication of frequency or intensity of activity. The interview questions asked about barriers and facilitators generally encountered by participants, finding that barriers and facilitators to physical activity participation fit broadly into two categories, namely, 1) individual influences related to the loss of an able identity and redefinition of self, which may have involved physical activity, and 2) societal influences including environmental and attitudinal barriers.[66]

In addition to accessibility of the physical environment, physical and mental health problems were also identified as key barriers to physical activity participation for individuals with SCI.[67] These findings were based on semi-structured interviews with 32 people with SCI (24 male, eight female, mean age 45 years, standard deviation 12) using 10 topic categories assumed to impact physical activity participation in individuals with SCI. Preparation and stimulation in the rehabilitation center for daily activities and social activities as well as support from family, friends and other people in society after discharge from rehabilitation were important facilitaors.[67] The authors did not specify the details of what preparation and stimulation entails.[67]

The factors impacting participation are interdependent, as emphasized by Kehn and Kroll (2009), who conducted semi-structured phone interviews with 26 individuals with SCI (ten females and sixteen males aged 23-74) to investigate experiences with exercise barriers and facilitators to being physically active. They identified similar barriers and facilitators identified in previous studies, and the participants emphasized the interdependence of motivational and socio-environmental factors.[68] The authors explained that no single factor predicts physical activity, but rather there is a unique combination of factors with varying levels of importance for each individual.

There are also some contrasting findings reported in the literature. Kinne (1999) created a model of variables predicting six-month maintenance of regular exercise based on data from a self-administered questionnaire in 113 adults aged 17-69 (47 males, 66 females) with long-term mobility impairments (16% had SCI). They found that in contrast with other findings, external barriers to exercise were not different between people who did and did not exercise, and that motivation and exercise self-efficacy were more predictive of exercise maintenance. They address, however, that this may be attributable to their method of participant recruitment from a specialized, supportive exercise group, or the relatively high levels of education of participants.[69] In addition, only 16% of participants had SCI.[69]

Overall, these findings provide insight into barriers and facilitators to physical activity participation experienced by individuals with SCI and reveal an opportunity for investigation of factors impacting physical activity during a wrist accelerometry physical activity monitoring period.

1.5.1 The social ecological model to understand factors impacting physical activity participation

We drew on a social ecological model of physical activity participation as an organizing framework to explore factors impacting physical activity participation. Social ecological models portray health behaviours as impacted by multiple interdependent levels of influence.[70,71] Specifically, physical activity as a health behavior can be promoted or inhibited by factors related to the individual and their social and physical environments.[70,71] This idea framed our approach to the question "What barriers and facilitators impact physical activity participation during a physical activity monitoring period for individuals with SCI?".

The social ecological model of health promotion behavior proposed by McLeroy and colleagues[71] was applied as an organizing theoretical framework by Martin Ginis and colleagues (2016) in their recent review of factors related to physical activity participation in individuals with physical disabilities.[70] Martin Ginis and colleagues propose the application of social ecological models to physical activity participation provides a useful framework for facilitating multi sector collaboration to promote physical activity participation.[70]

McLeroy's social ecological model of health promotion behaviour assumes that changing the social environment will elicit changes in the individual, and support of individuals is crucial to implement environmental changes.[71] The five levels of influence outlined by McLeroy include: intrapersonal, interpersonal, institutional, community and policy.[71] Additional levels of influence can be added as understanding of health behavior, in this case physical activity participation, changes.

Intrapersonal factors include characteristics of the individual.[71] Martin Ginis and colleagues reported that negative emotions, attitudes and self-perceptions were intrapersonal factors related to physical activity participation for individuals with physical disabilities.[70] The intrapersonal level also includes bodily factors such as secondary health issues, fitness and function.[70]

The interpersonal level outlined by McLeroy encompasses social networks and support systems such as family, friends and work groups.[71] Martin Ginis and colleagues reported social support, social processes such as role modelling, and societal attitudes as main categories of interpersonal factors related to physical activity participation for people with physical disabilities.[70]

Institutional factors include organized social institutions with formal or informal rules and regulations.[71] Martin Ginis and colleagues reported key factors at the institutional level related to physical activity participation for individuals with physical disabilities. Whether staff in institutions (e.g. community centres) have disability specific knowledge about physical activity affects participation for these individuals.[70] In addition, encouragement, counselling and information from professionals during the rehabilitation process were also important for participation.[71] The availability of physical activity programs and whether they were enjoyable were also key factors at the institutional level. Lastly, building accessibility was an important institutional level factor impacting physical activity participation.[70]

The community level of influence encompasses relationships among groups and organizations.[71] McLeroy defined community in three ways. First, community includes primary groups such as family, friend groups, teams, neighborhoods and voluntary associations.[71] Second, community refers to relationships between organizations and groups in a certain geographical area.[71] Third, community is conceptualized as groups defined in political and geographical terms.[71] Martin Gini and colleagues found that climate and products/technology were critical categories of factors related to physical activity participation at the community level.[70] Relationships among groups and organizations were identified in their review but were not highly cited.[70]

The policy level includes governmental laws and policies, as well as association and organizational policies.[71] Martin Ginis and colleagues identified government health policies, and systems, services and policies for transportation as key factors at this level related to physical activity participation for individuals with physical disabilities.[70] Financial costs to participants and training of staff within organization were important factors related to organizational policies.[70]

1.5.2 Strengths of the social ecological model

The social ecological model could help to understand how different sectors impact physical activity participation for people with SCI. The social ecological model recognizes the role of intrapersonal factors without overemphasizing individual responsibility or blaming the individual.[71] It may serve as a useful framework to inform development of testable hypotheses and interventions to improve participation in physical activity. Further, the social ecological model can accommodate other models and theories to help develop interventions at one level to target other levels.[71] There is also potential to add additional levels to the social ecological model as our understanding of physical activity participation improves. The McLeroy social ecological model differentiates between institutional and community factors, which is critical when discussing physical activity for people with SCI, as institution based physical rehabilitation and community based programs are key settings for physical activity participation for people with physical disabilities.[71] Thus, the social ecological model's strengths lie in both its specificity and flexibility.

1.5.3 Weaknesses of the social ecological model

There are potential ethical issues with applying the social ecological model. Specifically, McLeroy explained that strategies to increase health promoting behaviours, (i.e. physical activity participation) based on the social ecological model could potentially be viewed as coercive[71]. For example, corporate incentives for physical activity participation could be subtly coercive if viewed as related to job retention or promotion, and interventions using social support to increase participation could be coercive by using social influences to change behaviour. McLeroy explains that these approaches to physical activity may also be paternalistic, and argues that involving the target population (i.e. people with SCI) in the process of research and intervention may serve to minimize paternalism and coercion.

1.6 Physical activity guidelines for individuals with SCI

The current Canadian guidelines for physical activity participation for individuals with SCI were formed by Martin Ginis and colleagues (2011), by expert consensus based on a systematic review of the evidence for the effects of exercise on physical fitness.[72] The guidelines stipulate that adults with SCI should participate in a minimum of 20 minutes of moderate to vigorous intensity physical activity twice weekly and strength training twice a week. The expert panel systematically assessed the available literature on physical activity in individuals with SCI and determined that there was sufficient evidence to make recommendations on the amount and intensity of physical activity necessary to improve muscle strength and physical capacity for individuals with chronic SCI. There was, however, insufficient evidence to create guidelines specifying the physical activity necessary to improve body composition or health in this population.[72] The current Australian guidelines for exercise participation for individuals with SCI recommend a minimum of 30 minutes of moderate aerobic exercise at least five days a week, or a minimum of 20 minutes of vigorous aerobic exercise at least 3 days a week, as well as strength and flexibility training at least twice a week.[73] These ambitious recommendations are consistent with guidelines for individuals without SCI. This is based on the rationale that there is an absence of compelling evidence that the guidelines for able-bodied individuals should not be applied to the SCI population, despite the many unique considerations for these individuals.[73] Other physical activity guidelines have been published for the SCI population; however, they were not based on a standardized process for guideline development. For example, the guidelines put forth by the American College of Sports Medicine are not presented with supporting literature, and the authors do not specify whether the guidelines describe physical activity to improve fitness or to achieve other health benefits.[74] Jacobs and Nash (2004) published guidelines based on a narrative review that did not evaluate the quality of evidence.[75]

Pelletier and colleagues (2014) evaluated the effectiveness of the Canadian guidelines published by Martin Ginis and colleagues in a 16 week randomized controlled trial. Twenty-three individuals with SCI were randomized into a guidelines training group (n=12) and an active control group (n=11). The training group completed 20 minutes of moderate to vigorous intensity aerobic exercise twice a week on either an arm cycle ergometer or hybrid recumbent stepper, as well three sets of ten repetitions of 6 resistance-training exercises that covered all major muscle groups. The control group was active in a community exercise program twice weekly but was given no specific recommendations for physical activity participation. Peak aerobic capacity (VO_2 peak), aerobic endurance (70% of VO_2peak until exhaustion) tests, and strength (1 rep max for each strength exercise) were assessed pre and post training. There were significant increases in VO2 peak and submaximal power output as well as increases in the 1RM for three of the six exercises in the training group but not the control group. The authors concluded that while strength and cardiovascular fitness improved, health benefits and reduction of cardiovascular disease risk could not be assumed.[76]

1.7 Current physical activity levels in individuals with SCI

Several studies have examined physical activity levels in the SCI population. Dearwater and colleagues (1985) reported that individuals with SCI are generally less active than individuals who do not have SCI, and that those with tetraplegia were less active than people with paraplegia.[77] The generalizability of their results is limited, however, as the sample consisted of inpatients in a rehabilitation setting. Studies of habitual physical activity in people with SCI, measured with the Physical Activity Recall Assessment for people with SCI (PARA-SCI), found no difference between physical activity levels in individuals with paraplegia and tetraplegia.[78,79] This may, however be partly attributable to the PARA-SCI's broad definition of lifestyle activity as well as the subjective classification of activity intensity by the PARA-SCI. Tawashy and colleagues found a large portion of physical activity for individuals with SCI was comprised of activities of daily living.[78] In their study of 158 men and women with SCI, Latimer and colleagues (2006) found that the mean daily minutes of moderate and heavy physical activity determined using PARA-SCI were 71.45 and 15.80, respectively.[79] Van den Berg-Emons and colleagues (2008) measured physical activity in people with SCI at various time points after active inpatient rehabilitation using multiple accelerometers mounted on different body locations for a 48 hour period. Their results showed that one year post discharge from inpatient rehabilitation, 16 participants engaged in dynamic activities such as manual wheeling, hand cycling and general movement for an average of 3.4 % of a 24 hour period, equal to 49 minutes a day.[80] They did not classify activity intensity or minutes of MVPA. Warms and Belza (2004) measured physical activity with wrist based accelerometry in 16 participants with SCI and reported physical activity in terms of total counts representing total daily activity but did not include a measure of activity intensity or minutes of MVPA.[81] Further research utilizing objective measures of activity duration and intensity is needed to quantify physical activity levels in individuals with SCI.

1.8 Physical activity measurement

1.8.1 Subjective measures of physical activity in individuals with SCI

Various surveys exist for physical activity measurement in SCI.[82–84] The PADS and the PASIPD are two commonly used methods to date; however, both are limited with respect to the intensity domain. The PADS assesses intensity of structured exercise but not of leisure activities or activities of daily living, and the PASIPD uses standard MET values to classify intensity, which is inappropriate for individuals with SCI because of lower resting energy expenditure.[84] The best measurement tool we currently have for measuring physical activity in individuals with SCI is the PARA-SCI.[85] The PARA-SCI is a measure specifically designed and validated for people with SCI. Although it incorporates a protocol for reporting the intensities of all activities performed in the previous three days, data collection is still limited by the participant's recall ability.[84] Participants may either over or under estimate physical activity, and it can be especially difficult to recall low intensity activities, which can make up a large portion of daily physical activity.[86,87] In the 2003-2004 National Health and Nutritional Examination Survey in the USA, 51% percent of adults met the physical activity guidelines based on self-report measures, when less than 5% met the guidelines according to accelerometry data.[87]

1.8.2 Objective measures of physical activity in individuals without SCI

An accelerometer is a small, portable device that can be worn on the body to measure movement acceleration in one or more planes. Hip accelerometry is the industry standard for physical activity measurement in individuals who do not have SCI. In individuals who do not use wheelchairs, numerous calibration studies have yielded general accelerometry 'cut-points' that can be used to categorise the movement signal values obtained from accelerometers into relevant health-related physical activity intensities (e.g., the values can be categorized as representing low, moderate or vigorous intensity activity).[88,89] These cut-points have typically been identified relative to energy expenditure determined through indirect calorimetry and are used to classify physical activity intensities across individuals in an entire population.[88,89] Although such cut-points are widely used in physical activity research, some have argued that individualised accelerometry cut points are warranted in special populations, for example older adults with altered biomechanics and/or lower cardiorespiratory fitness.[90]

1.8.3 Objective measures of physical activity in individuals with SCI

Multiple objective measures of physical activity have been applied in wheelchair users, for example, revolution counters[91] and odometers.[92] These devices are limited to capturing only wheeled activity and thus do not capture many non-wheeled activities and can misrepresent the intensity of wheeling, for example on different surfaces or during passive downhill coasting. For this reason, a device that is placed on an individual's body is likely to more accurately represent physical activity.

Hiremath and Ding (2011) evaluated the energy expenditure estimated by the SenseWear Armband accelerometer, worn on the upper arm, and the RT3 tri-axial trunk accelerometer in 24 individuals with paraplegia. Participants wore the two accelerometers, a portable metabolic cart and a heart rate monitor during rest, wheelchair propulsion, arm ergometry exercise, and deskwork. Energy expenditure estimated by the accelerometers was compared to the energy expenditure measured via metabolic cart. Agreement between the methods was assessed using intraclass correlations and Bland Altman plots. Energy expenditure estimation errors for the SenseWear ranged from 24.4% to 125.8%, and based on low intraclass correlations and high absolute and percent error, the authors concluded that neither accelerometer was an appropriate tool to measure physical activity in manual wheelchair users. Interestingly, they did find that there was a higher correlation between the energy expenditure measured by the arm accelerometer and the metabolic cart than the trunk accelerometer and metabolic cart. They could not determine whether this was attributable to the location of the device as the two devices were quite different. A key limitation to this study is that the algorithms used to estimate energy expenditure from the accelerometers were based on individuals who do not have SCI.[93]

Hiremath and colleagues (2012) completed another study in order to develop SCI specific prediction models for energy expenditure in manual wheelchair users based on the SenseWear activity monitor. This monitor included a 2-axis accelerometer, galvanic skin response sensor, skin temperature sensor and near-body temperature sensor. Forty-five participants completed the same activities described above while wearing the monitor. Two energy expenditure prediction models were developed based on the raw 16Hz accelerometer data, one minute averages of the other variables, and demographic information. The first prediction model included one general equation for all physical activity, and the second included an activity specific equation for each type of physical activity completed. The equations were developed using data from 36 of the participants and evaluated on the remaining nine participants. The authors found that the new models significantly improved energy expenditure prediction compared to the manufacturer's model.[94]

Conger and colleagues (2015) assessed this model established by Hiremath et al (2012). They evaluated the ability of both the SenseWear arm accelerometer and the Actical wrist worn accelerometer to detect energy expenditure changes in response to wheeling at varying speeds and on different surfaces by fourteen manual wheelchair users, seven of which had SCI. Participants wheeled on a level surface at three speeds, on a rubberized track at a fixed speed and on a sidewalk at a self-selected speed, while wearing the accelerometers and a portable metabolic cart. The authors compared wheelchair propulsion energy expenditure estimated via indirect calorimetry to the energy expenditure calculated from standard prediction equations for these devices based on able-bodied individuals, and for the SenseWear, the authors also applied the SCI specific equation established by Hiremath and colleagues (2012), described above. They found that the SenseWear overestimated energy expenditure during wheeling activities, and while the Hiremath (2012) equation improved this, the error was still large and increased during higher intensity activities. The authors also found that the Actical wrist worn accelerometer could differentiate between energy expenditure during wheeling at different speeds and surfaces. The energy expenditure estimates from the Actical were not significantly different from the energy expenditure measured by the metabolic cart, but the individual error was still relatively high.[95]

Tanhoffer and colleagues (2012) compared various methods of estimating physical activity and energy expenditure to the doubly labeled water technique in fourteen manual wheelchair users with SCI. The doubly labeled water technique was used to determine total daily energy expenditure over 14 days. Participants wore a Polar heart rate monitor and SenseWear arm accelerometer for two days. They also completed the PARA-SCI and PASIPD to evaluate physical activity completed during the three immediately prior days. Physical activity energy expenditure was estimated by subtracting each participant's measured basal metabolic rate measured via open circuit spirometry and the estimated thermic effect of food from total daily energy expenditure. The thermic effect of food was assumed to be 10% of total daily energy expenditure. The estimated total daily energy expenditure and physical activity energy expenditure from all methods was compared to the reference values determined through doubly labeled water. It was found that the PARA-SCI best estimated total daily energy expenditure (r=0.74) and physical activity energy expenditure (r=0.5). There was a weaker correlation between PASIPD and doubly labeled water for total daily energy expenditure (r=0.53) and physical activity energy expenditure (r=0.13). There was a moderate correlation for total daily energy expenditure between the heart rate methods and doubly labeled water (r=0.68) and a poor correlation for physical activity energy expenditure (r=0.3). There was a moderate correlation for total daily energy expenditure between SenseWear and doubly labeled water (0.65), but a weak correlation for physical activity energy expenditure (r=0.16). This may not be surprising given that physical activity energy expenditure based on 2 days of accelerometer and heart rate monitor wear was compared to the doubly labeled water measure of 14 days. Another limitation is that this study used able-bodied algorithms to estimate energy expenditure with the SenseWear accelerometer.[85]

Warms and Belza (2004) assessed the feasibility, suitability and validity of the ActiGraph wrist accelerometer as a method to measure habitual physical activity in individuals with SCI. The study consisted of 3 phases. Phase one was a pilot test during which six participants wore the monitor in controlled conditions, including five minutes each of indoor wheelchair pushing, upper extremity range of motion activities, sitting with arms in the lap and sitting doing key-board activities. For phase two, the same six participants wore the accelerometer for 4 days of daily physical activity monitoring. They also completed a self-report activity log. Phase 3 consisted of the same activity monitoring as phase 2, completed twice by 16 participants, separated by an intervention designed to increase physical activity. Twenty-two participants in total completed daily physical activity monitoring. There was high adherence during the monitoring period, with a mean of 95% wear time. Participants rated the physical comfort of the device, amount of interference with daily activities and willingness to wear the Actiwatch again, and the results indicated an acceptable level of participant burden. The correlation coefficients between accelerometer derived activity counts and self-report activity ranged from 0.3 to 0.77, with a mean correlation of 0.6. There was also concurrence between intensity measured by self-report and the magnitude of activity counts. While these results may be favourable, the strength of validating an objective measure against a self report measure is questionable.[81]

Postma and colleagues (2005) sought to determine whether wheelchair propulsion and other activities could be validly detected using multiple accelerometers at different body locations by validating this method against video recording in individuals with SCI.[96] They were also interested in the whether varying triceps strength of individuals with SCI would affect the validity of the activity monitors. Participants included eight rehabilitation inpatients and two outpatients with paraplegia or tetraplegia, five of whom had poor triceps strength and five who had good triceps strength. They were outfitted with an activity monitor that consisted of six accelerometers at different body locations, including both wrists and thighs, and over the sternum. Participants wore a data recorder attached to a belt around the waist. They completed wheeled and non-wheeled activities that could possibly be falsely detected as wheelchair propulsion, for 2-4 minutes per activity, while being video recorded. The video recording and activity monitor data were synchronized and analyzed and the overall agreement between the two methods was high, ranging from 87-96%, with a mean of 92%. Sensitivity to wheelchair propulsion was lower in the group with poor triceps strength compared to good triceps strength (81% and 95% respectively). The activity monitor overestimated wheelchair propulsion duration by only 3.9% overall, with a larger overestimation in the subgroup with strong triceps. The authors conclude that the activity monitor can be used to validly detect wheelchair propulsion in individuals with SCI with both poor and good triceps strength.[96] While these results are favourable, it is not feasible for participants to wear six accelerometers for daily habitual physical activity monitoring, and there was also no quantification of activity intensity.

Kooijmans and colleagues (2014) assessed the validity of a less complex objective method of measuring physical activity in individuals with SCI, which employed two accelerometers.[97] Ten males with paraplegia or tetraplegia were outfitted with two ActiGraph GT3X accelerometers; one each on the wrist and one on the wheelchair spokes. Sampling frequency was 30Hz and epoch length was one second for analyses. Participants then completed self-propelled wheeling as well as activities that could possibly be falsely detected as wheeling in a laboratory setting while being video recorded. Accelerometer data was analyzed using an algorithm that the researchers developed to differentiate between self-propelled wheeling and other activities based on vector magnitude counts. Briefly, cut-points were set for both the wrist and spoke accelerometer vector counts and the settings for the algorithms were based on unspecified test measurements performed in both wheelchair users and non-wheelchair users. Agreement between video analysis and accelerometer data was 85.2%, ranging from 76.7% to 92.3% per measure. The sensitivity and specificity for detecting self-propelled wheeling were

88.3% and 83.3%, respectively. The authors conclude that this combination of a wrist accelerometer, spoke accelerometer and their algorithm provided a valid measure of duration of self-propelled wheeling. This method has greater potential for daily physical activity monitoring than the six-accelerometer activity monitor method used by Postma and colleagues (2005) as the participant burden would be lower, and the set-up less complex. There was still however, no measure of intensity of physical activity intensity.[97]

1.9 Summary

Spinal cord injury disrupts the sympathetic nervous system, leading to level and severity of injury dependent cardiovascular dysfunction. The combination of cardiovascular dysfunction and physical inactivity in individuals with SCI leads to an increased prevalence of CVD risk factors, including dyslipidemia, increased CRP levels, abdominal obesity, visceral adiposity and type II diabetes. Put together, these factors result in cardiac atrophy and impaired systolic function, likely explaining the greatly increased odds of heart disease observed in this population. Encouragingly, preclinical and clinical studies show that exercise training can partially reverse cardiac dysfunction after SCI. While physical activity may confer similar benefits, studies that have investigated the relationship between cardiac function and physical activity in individuals with SCI have relied on subjective measures. This is an important limitation as subjective measures are confounded by recall ability and thus make it difficult to empirically establish a relationship between physical activity and cardiac function. As such, an objective measure of physical activity is needed to better elucidate the relationship between physical activity and cardiac function, and to help create evidence based guidelines for physical activity participation aimed at improving cardiac health. Moreover, additional qualitative insight into the barriers and facilitators of physical activity participation in individuals with SCI is likely to aid the scientific community in understanding how to best encourage this population towards better health.

1.10 Objectives

The objectives of this thesis, therefore, were: 1) to objectively measure physical activity in individuals with SCI, using wrist-worn accelerometry during a six-day physical activity monitoring period, and to evaluate the utility of group based wrist accelerometry cut-points to estimate physical activity intensity by comparing MVPA determined by individual cut-points to MVPA determined by group-based cut-points; 2) to determine the relationship between objectively measured physical activity and cardiac structure and function in individuals with SCI across a range of injury levels, and 3) to explore the barriers and facilitators to physical activity participation experienced by individuals with SCI during a six-day physical activity -monitoring period.

Chapter 2: Individual physical activity cut-points for wrist accelerometry in individuals with spinal cord injury

2.1 Introduction

Cardiovascular disease is the leading cause of death in people with SCI and the odds of heart disease and stroke in this population are greatly increased relative to the general population.[4] Physical inactivity is posed as an important risk factor for these increased odds of chronic disease development.[4] Physical activity is defined as "any bodily movement produced by skeletal muscles that results in energy expenditure".[98] Physical activity has been shown to decrease chronic disease risk in people with SCI.[13,62] Current guidelines for physical activity participation in SCI were formed by expert consensus based on a systematic review of the evidence for the effects of exercise on physical fitness.[72] There are currently no SCI population-level data on how physical activity is related to chronic disease risk factors, and thus, no evidence-based guidelines for using physical activity to reduce chronic disease risk as we have for the general population.[99] In order to obtain these data for people with SCI, an important step is to develop a valid measure of physical activity that can be used in SCI population health surveillance studies.

Physical activity measurement in people with SCI can be conducted using a variety of methods including self-report as well as electronic devices such as revolution counters and accelerometers. In able-bodied individuals, hip-worn accelerometry is the industry standard for objectively measuring daily physical activity as it is related to overall energy expenditure and is captive of typical bodily movements such as walking.[100] No such industry standard currently exists for objective physical activity measurement in people with SCI. The best measurement tool currently available for measuring physical activity in individuals with SCI is the PARA-SCI, which is specifically designed and validated for this population.[85] Although it incorporates a protocol for reporting the intensities of all activities performed in the previous three days, data collection can be limited by recall ability.[84]

In wheelchair users with various disabilities, wheel revolution counters and spoke accelerometers have been used to measure distance and speed travelled in a wheelchair.[91,92] However, such devices may misrepresent the intensity of some wheeled activities such as assisted wheeling or passive downhill coasting. Further, these wheelchair-mounted devices would not capture non-wheeled activity (e.g., use of a wall-mounted arm ergometer or washing dishes). For these reasons, devices measuring upper extremity movement, such as wrist-worn accelerometers, are likely better objective measures of physical activity in people with SCI. To date, wrist-worn accelerometers have been used in people with SCI, and strong associations between accelerometer counts and energy expenditure during graded wheelchair exercise or simulated activities of daily living have been reported.[95,101–103] Moreover, a wrist-worn accelerometer cut-point that equates to moderate-to-vigorous physical activity (MVPA) has been proposed for wheelchair users.[104] It is unclear, however, whether the use of a single cut-point is valid for determining habitual MVPA in people with SCI. In this respect, some have argued that individualized accelerometry cut-points are warranted in special populations, for example older individuals with altered biomechanics.[90] Given individuals with SCI experience varied autonomic, motor, and sensory impairments it is plausible that SCI individuals represent another population for which individualized cut-points are warranted.

With the long-term goal of being able to use accelerometry in population-level physical activity and health-monitoring studies of people with SCI, the aims of the present study were to:

1) perform a calibration study to create individual and group-based cut-points for wrist-accelerometry that correspond to energy expenditure equivalent to MVPA; 2) to investigate the potential utility of the group-based cut-points for classifying physical activity intensities by comparing MVPA as calculated by individual and group cut-points during an habitual physical activity monitoring period.

2.2 Methods

2.2.1 Participants

A convenience sample of individuals with SCI was recruited from the Metro Vancouver area, Canada. Participants were recruited through posters at the Blusson Spinal Cord Centre and GF Strong Rehabilitation Centre in Vancouver, at SCI community events and by contacting participants from previous studies who had indicated they would like to be contacted for future studies. The majority of participants were members of the Physical Activity Research Centre at the Blusson Spinal Cord Centre. Inclusion criteria were: (a) having sustained a traumatic SCI at least one year prior, and (b) 18-65 years of age. Exclusion criteria were: (a) any history and/or symptoms of cardiovascular or cardiopulmonary disease or problems; (b) major trauma or surgery within the past 6 months; (c) an active stage 3 or 4 pressure ulcer; (d) any unstable medical/psychiatric condition that were likely to affect ability to complete the study; (e) lack of proficiency in the English language that would prevent ability to follow instructions. Twenty-two manual wheelchair users completed the study. Participants were 31-64 years old (20% female) and 1.2-43.0 years post injury, with injury level ranging from C5-L2. Each participant provided written informed consent and ethics approval was granted by the University of British Columbia Clinical Research Ethics Board.

2.2.2 Overview of the protocol

Testing consisted of a 2-hour laboratory session (calibration study) followed by a six-day habitual physical activity monitoring period. During the laboratory visit, participants completed a submaximal graded treadmill wheeling test which involved wheeling at ≥3 different speeds while connected to a metabolic cart, wearing an accelerometer on the wrist, and with a wheelchair spoke accelerometer fitted. Participants were then asked to wear the wrist and wheelchair spoke accelerometers continuously over the next six days to capture daily physical activity. If participants used two different chairs during their week then a separate spoke accelerometer was attached to each chair.

2.2.3 Treadmill wheeling test

Each participant was weighed on a wheelchair scale (PUA220A Mettler Toledo, Bradford, MA). The participants performed a submaximal graded wheeling test on a treadmill suitable for wheelchairs (MAX Mobility LLC, Antioch, TN). Each participant used his/her own wheelchair, which was secured to the treadmill with safety straps attached above both front casters. Participants were fitted with a chest heart rate monitor strap (Polar Electro H1 Heart Rate Sensor, Kempele, Finland), wrist-worn accelerometer on the non-dominant arm (GT9X link, ActiGraph, LLC, Pensacola, FL; 30 Hz), wheelchair spoke accelerometer (USB Accelerometer X16-1D, Gulf Coast Data Concepts, LLC, Waveland, MS) on the same side as the non-dominant arm, nose clip, and mouthpiece attached to a metabolic cart (Parvo Medics TrueOne 2400, Sandy, UT). The test protocol commenced with three to five minutes of quiet rest while seated in the wheelchair, followed by ≥3 incremental exercise stages of four-minute duration. The treadmill speeds were self-selected from 1-7 km/hr based on individual preference, with the aim of completing four minutes of continuous wheeling at a minimum of three different intensities.

Mixed expired breath-by-breath oxygen uptake, wrist-acceleration and wheelchair spoke-acceleration were measured continuously throughout the test. Participants completed the test either continuously or with breaks based on preference; if the latter, the mouthpiece and nose clips were removed for a one to three-minute rest period between stages.

2.2.4 Physical activity monitoring period

Participants were fitted with the wrist-worn accelerometer and instructed to wear it for 6 days, only removing it for bathing/swimming and for sleeping if they experienced discomfort. The wheelchair spoke accelerometer was attached to the wheelchair spokes and was not removed during the monitoring period. In order to maximize compliance, text or email reminders were sent every morning to remind participants to wear the accelerometer. The wrist-worn accelerometer displayed the time of day only and the spoke accelerometer had no display.

2.2.5 Analyses

2.2.5.1 Cut-point calibration

One second epoch .agd files were generated from the raw .gt3x triaxial wrist accelerometry file using ActiLife v6.12.0 and vector magnitude (SQRT[(Axis 1)^2 + (Axis 2)^2 + (Axis 3)^2]; counts per minute (VM-CPM)) was chosen as the primary outcome measure of physical activity. Wheelchair accelerations from two orthogonal axes coplanar with the wheel were filtered with a 2nd order low-pass Butterworth filter (cut-off frequency of 3.1 Hz). Wheel rotation angle was determined as the inverse tangent of the ratio of the two filtered accelerations. Wheelchair speed (m/s) was calculated as the derivative of rotation angle multiplied by wheel circumference, then filtered using a 2nd order low-pass Butterworth filter (cut-off frequency of 0.5 Hz).[105]

Oxygen consumption (ml/kg/min), wrist-acceleration vector magnitude (VM-CPM), and wheelchair speed (m/s) were averaged across the penultimate 30s of each exercise stage.

‘Moderate-to-vigorous intensity’ typically refers to an energy cost of ≥3 metabolic equivalents (METs; multiples of resting metabolism).[106] A standardized value of 3.5ml/kg/min is defined as 1 MET for an adult without SCI.[106] Application of this MET value would likely overestimate resting energy expenditure and under estimate activity intensity in individuals with SCI.[107] Thus, oxygen consumption was divided by 2.7ml/kg/min to convert to SCI METs.[107] Linear regression was used to identify the wrist acceleration vector magnitude (VM-CPM) corresponding to an energy expenditure of 3 SCI METS (8.1ml/kg/min) in each individual to define the individual MVPA cut-point. Multilevel linear regression was applied to determine the group MVPA cut-point such that multiple observations per participant were accounted for.

2.2.5.2 Comparison of individualized versus group cut-points for wheeled and non-wheeled activity

Habitual physical activity monitoring at the wrist was deemed valid if wrist-worn accelerometer wear time exceeded 600 min/day on 3 or more days (ActiLife v. 6.12.0). Filtered wheelchair speed was time-aligned to wrist acceleration vector magnitude from valid days to enable the separation of wheeled vs. non-wheeled MVPA. During MVPA measured at the wrist, time (s) spent at speeds equal or greater than 0.12m/s was considered to be wheeled MVPA.[105] Non-wheeled MVPA was defined as the difference between total MVPA and wheeled MVPA. Time spent during wheeled MVPA, non-wheeled MVPA and total MVPA was summed for each valid day of monitoring and then averaged across all valid days and expressed as mean minutes per day. This was done twice for each participant; once using the individual wrist-worn accelerometer cut-point and once using the group cut-point. We assessed agreement in measures of MVPA (total, wheeled, non-wheeled) between cut-point methods using Bland-Altman analyses (GraphPad Prism Version 6.05). Differences between wheeled MVPA, non-wheeled

MVPA, and total MVPA (individual cut-points only) were evaluated using a repeated-measures ANOVA with Bonferroni corrected pairwise comparisons.

2.3 Results

Of 22 participants, 21 had sufficient treadmill wheeling data (≥3 stages) to perform linear regression to establish an individual wrist-worn accelerometer cut-point. One participant failed to meet the wrist-worn accelerometer wear time requirements for the 6d activity-monitoring period resulting in an analytical sample of 20 participants. Because three participants did not have sufficient spoke accelerometer data due to technical error, the breakdown of MVPA into wheeled and non-wheeled activity was determined for only 17 participants. Using regression analyses, a vector magnitude (VM-CPM) equivalent to 3 SCI METs (i.e., MVPA threshold) was calculated for each individual. The individual MVPA cut-points ranged from 6040 to 21540 VM-CPM and mixed-model regression analyses revealed the group MVPA cut-point was 11652 (CI 7395 – 15909; Fig 2.1).

2.3.1 Physical activity monitoring period

The daily mean times spent in total MVPA, wheeled MVPA, and non-wheeled MVPA for each participant during the monitoring period are reported in Table 2.1. Bland-Altman analyses of differences between daily mean total MVPA determined by individual cut-points and group mean cut-points revealed a bias of 0.22 ± 33.0 minutes, with 95% limits of agreement from -64.5 to 64.9 minutes (Fig 2 panel A). Bland-Altman analyses of differences between daily mean wheeled and non-wheeled MVPA determined by individual cut-points and group mean cut-points revealed biases of -0.9±7.9 minutes and -0.77±23.11 minutes, respectively, with 95% limits of agreement from -16.53 to 14.6 and -46.1 to 44.5 for wheeled and non-wheeled MVPA, respectively (Fig 2.2, panels B and C). These results suggest a large discrepancy in MVPA derived from individual vs. group mean cut-points. The amount of time spent in non-wheeled MVPA was significantly higher than the amount of time spent in wheeled MVPA (Table 2.1).

Table 2.1. Participant characteristics and mean daily total moderate-to-vigorous physical activity (MVPA)

Participant #	Injury Level	Sex	Total MVPA (min/day)	Wheeled MVPA (min/day)	Non-wheeled MVPA (min/day)
1	C5	M	110.8	26.0	84.8
2	C5	M	38.5	8.0	30.5
3	C5	M	18.1	8.3	9.8
4	C5	M	97.7	n/a	n/a
5	C5	M	130.9	46.5	84.4
6	C5	M	24.6	4.9	19.7
7	C6	F	15.7	n/a	n/a
8	C6	M	37.5	8.4	29.1
9	C7	M	60.3	8.9	51.4
10	T3	M	34.6	4.2	30.4
11	T4	M	104.0	n/a	n/a
12	T4	M	64.6	15.5	49.1
13	T4	F	4.6	1.0	3.6
14	T5	F	57.1	9.9	47.3
15	T5	M	77.3	17.9	59.5
16	T11	M	92.4	14.4	78.0
17	T12	M	57.5	9.0	48.5
18	T12	M	61.4	5.8	55.7
19	T12	M	96.3	24.8	71.5
20	L2	F	50.7	5.4	45.3
Mean			61.7	12.9*	47.0*†
SD			35.06	11.1	24.4
Maximum			130.9	46.5	84.8
Minimum			4.6	1.0	3.6

MVPA based on individual cut-points. Between-MVPA type comparisons computed for n=17; *p<0.001 vs. total MVPA; † p<0.01 vs. wheeled MVPA.

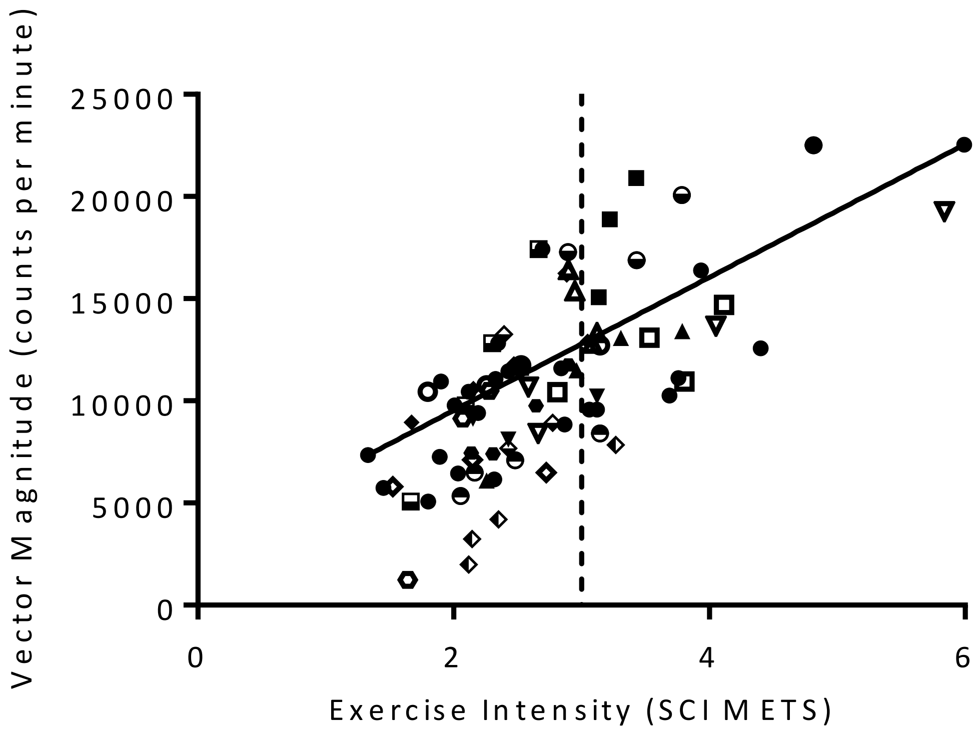

Figure 2.1. Association between exercise intensity in SCI metabolic equivalents (METS) and vector magnitude (VMCPM) derived from the wrist-worn accelerometer. Each symbol shape represents one participant. The solid line represents the multilevel regression. The dashed vertical line at 3 SCI METS represents the cut-point for moderate-to-vigorous physical activity.

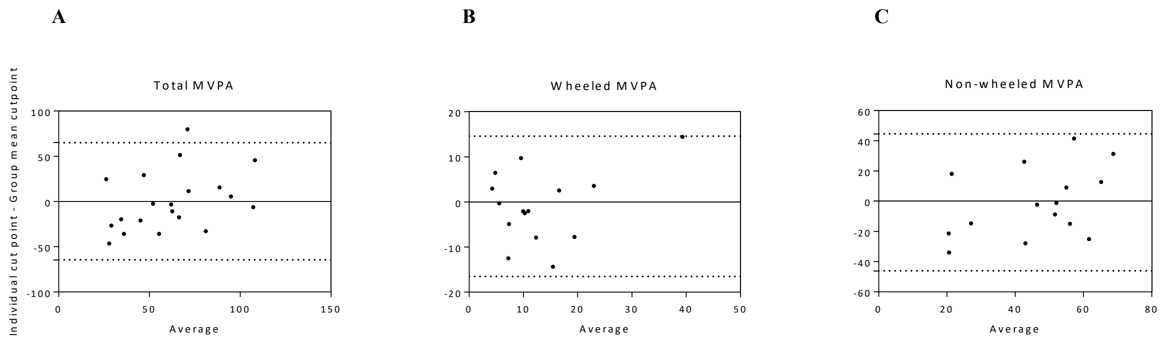

Figure 2.2. Bland-Altman plot comparing group mean cut-point moderate-to-vigorous physical activity (MVPA) to individual cut-point values, for total MVPA (panel A), wheeled MVPA (panel B) and non-wheeled MVPA (panel C). Note the variability between individual and group mean cut-points for determining minutes spent in all MVPA types. Dotted lines represent 95% limits of agreement

2.4 Discussion

The main finding of this study was that individual MVPA cut-points were highly variable between participants meaning that the use of a group mean accelerometer cut-point under- or over-estimates total daily MVPA by -46 to +80 minutes per day. Habitual physical activity monitoring revealed that individuals with SCI obtained most of their MVPA during non-wheeled activities.

2.4.1 Group cut-points do not accurately reflect MVPA in individuals with SCI

The misrepresentation of minutes spent in MVPA when applying group mean cut-points is a result of the wide range of individual wrist-worn acceleration profiles that correspond to 3 SCI METs. This variation is likely due to differences in participants' metabolic response to exercise, which may be attributable to differences in body composition and neurological level/severity of injury. In this respect, a previous study found lower energy expenditure in individuals with complete cervical SCI vs. incomplete cervical SCI during outdoor wheeling, as well as higher energy expenditure during arm-cranking in those with paraplegia.[107] The amount of body muscle mass and the percent of muscle mass that is active also varies between individuals based on injury level and severity, whereby those with the highest and most severe injuries have the lowest amount of active muscle.[108] The present study intentionally included a wide range of injury levels, which likely resulted in a range of resting metabolic rates and varying MET-accelerometry relationships. Additionally, differences in wheeling experience, skill level and strength of the muscles involved in wheelchair propulsion may have resulted in biomechanical efficiency varying between participants.[109] For the above reasons, we suggest it is inappropriate to apply a generalized accelerometry cut-point to wrist-worn accelerometer data to estimate MVPA duration and intensity in individuals with SCI. Individual cut-points should be applied when using wrist accelerometry to study MVPA in this population.

2.4.2 Individuals with SCI exhibit variation in their daily MVPA levels

We found individuals on average performed approximately one hour of MVPA per day, although there was considerable variation with some individuals performing as little as four minutes and others as much as three hours. These results are broadly in agreement with prior studies that have reported daily activity levels in people with SCI using accelerometers or the PARA-SCI. Van den Berg-Emons and colleagues (2008) measured physical activity in people with SCI one year post discharge from inpatient rehabilitation using accelerometry.[80] Results showed that participants engaged in dynamic activities such as manual wheeling, hand cycling and general movement for an average of 3.4 % of a 24-hour period, equal to 49 minutes a day.[80] It is difficult, however, to directly compare these results to the present study as they did not apply cut-points or report minutes of MVPA. Using the PARA-SCI, Latimer and colleagues (2006) reported that the mean daily minutes of moderate and heavy activity were 85 minutes (sd = 96 mins for moderate activity) of which only 25% was obtained during leisure time activity.[79] Tawashy et al., (2009) reported that mean daily minutes of moderate and heavy activity was 98 minutes (sd = 149 mins for moderate activity) of which 50% was obtained during leisure time activity.[78] In our sample, the majority of MVPA was obtained during activities other than wheeling. Unfortunately, accelerometers cannot separate leisure time activity from activities of daily living so it is unknown which type of activity comprised the majority of MVPA in our sample. Further, differences in sample size, sampling method, and recruitment between studies make direct comparisons to our results difficult to interpret. Nevertheless, taken together our data and that of others imply that individuals with SCI exhibit extremely varied amounts of daily MVPA that is obtained from both wheeled and non-wheeled activities that span both leisure time activity as well as activities of daily living.

2.4.3 Study limitations

While accelerometry eliminates the issue of physical activity recall ability, there are considerations when extrapolating cut-points from treadmill wheeling in a laboratory setting to estimate intensity of physical activity during non-wheeling activities of daily life, and non-wheeling exercise activities. For example, the intensity of washing dishes, getting dressed or strength training may be misrepresented. This study included only people who used manual wheelchairs, for whom the intensity of outdoor wheeling on rough surfaces may have been misrepresented by the wrist-worn and wheelchair spoke accelerometers due to differences in rolling resistance. Similarly, the intensity of wheeling uphill is likely misrepresented by wrist-worn and wheelchair spoke accelerometry; a key consideration given the study took place in the hilly city of Vancouver. For this reason, we suggest wrist-worn accelerometry and wheelchair spoke accelerometry as measures of physical activity should be supplemented with subjective and/or other objective measures to gain additional insight into the types and contexts of physical activity. Furthermore, the SCI MET value of 2.7 ml/kg/min used here was applied based on a study that measured resting energy expenditure of 66 individuals with SCI.[107] Collins and colleagues found no statistically significant difference between resting energy expenditure values for those with high (C5-C8) vs. low injury levels (T1-L4), but energy expenditure was slightly lower in high-level SCI, suggesting physical activity may have been over- or under- estimated in some participants.

2.5 Conclusion

The use of group cut-points misrepresented daily MVPA when compared to individual cut-points. Our data suggest that individual calibration of wrist-worn accelerometry against energy expenditure should be performed ahead of habitual physical activity monitoring due to the considerable heterogeneity in the association between physical activity and energy expenditure in individuals with SCI.

Chapter 3: Physical activity is related to cardiac function in individuals with spinal cord injury

3.1 Introduction

Spinal cord injury (SCI) is a devastating condition affecting an estimated 86 000 individuals in Canada, posing a significant burden on our health care system.[110] While short term survival within the first two years post SCI has improved since the 1970s,[111] long term survival after SCI has not improved,[112] and cardiovascular disease remains the number one cause of death in this population.[113]

Individuals with SCI are at greatly increased risk and odds of heart disease.[4,113] People with SCI exhibit cardiac dysfunction characterized by left ventricular atrophy,[42,43] impaired systolic function,[42,53] electrocardiogram abnormalities,[114] inability to respond to ischemia,[115] resting bradycardia,[2] and increased risk of reperfusion induced arrhythmias.[116,117] Multiple mechanisms may lead to cardiac changes following SCI, including beta-adrenergic hypersensitivity[31] and the loss of supraspinal control of sympathetic input to the heart and vasculature,[27,56] causing disrupted blood pressure control,[32] reduced blood volume,[36] and a reduction in venous return. These factors ultimately result in unloading of the left ventricle, which is exacerbated by immobility.[118] Generally, the severity of cardiac dysfunction is related to the level of SCI, whereby individuals with tetraplegia exhibit the most dysfunction.[42]

Exercise training is a method to reverse cardiac dysfunction in individuals with SCI.[58–60] In fact, studies in rats and humans have shown that exercise training following SCI can reverse left ventricular atrophy and attenuate dysfunction.[56,58–60] Whether habitual daily physical activity confers a similar benefit for cardiac function as exercise is unclear. Previous work has found better cardiac structure with higher physical activity levels in people with SCI, however physical activity was measured using subjective and recall based measures.[44,45] Wrist worn accelerometry is a method to objectively measure physical activity in individuals with SCI. Strong associations between wrist accelerometer counts and energy expenditure during graded wheelchair exercise or simulated activities of daily living for people with SCI have been reported ,[95,101–103] however, no study has examined relationships between objectively measured habitual daily moderate-to-vigorous physical activity (MVPA) and cardiac indices in individuals with SCI. The aim of this study, therefore, was to address this gap in the literature and determine whether there is a relationship between objectively measured MVPA and indices of cardiac structure and function in individuals with SCI across a range of injury levels, and to see if this potential relationship is independent of the expected differences by injury level.

3.2 Methods

3.2.1 Participants

A convenience sample of individuals with SCI was recruited from the Metro Vancouver area, Canada. Participants were recruited through posters at the Blusson Spinal Cord Centre and GF Strong Rehabilitation Centre in Vancouver, at SCI community events and by contacting participants from previous studies who had indicated they would like to be contacted for future studies. The majority of participants were members of the Physical Activity Research Centre at the Blusson Spinal Cord Centre. Inclusion criteria were: (a) having sustained a motor complete traumatic SCI at least one year prior, and (b) 18-65 years of age. Exclusion criteria were: (a) any history and/or symptoms of cardiovascular or cardiopulmonary disease or problems; (b) major trauma or surgery within the past 6 months; (c) an active stage 3 or 4 pressure ulcer; (d) any unstable medical/psychiatric condition that were likely to affect ability to complete the study; (e) lack of proficiency in the English language that would prevent ability to follow instructions. Eighteen manual wheelchair users completed the study. Participants were 31-64 years old (23% female) and 1.2-43.0 years post injury, with injury level ranging from C5-L2 (tetraplegia n=8 and paraplegia n=9). Each participant provided written informed consent and ethics approval was granted by the University Clinical Research Ethics Board.

3.2.2 Overview of the protocol

Testing consisted of two 2-hour laboratory sessions separated by a six-day habitual physical activity monitoring period. During the first laboratory visit, participants completed a sympathetic skin responses and a submaximal graded treadmill wheeling test which involved wheeling at ≥3 different speeds while connected to a metabolic cart, wearing an accelerometer on the wrist, and with a wheelchair spoke accelerometer fitted. This test permitted individual cut-point calibration of the wrist accelerometer for physical activity measurement. Participants were then asked to wear the wrist and wheelchair spoke accelerometers continuously over the next six days to capture daily PA. If participants used two different chairs during their week then a separate spoke accelerometer was attached to each chair. During the second laboratory visit, an echocardiographic assessment was performed.

3.2.3 Laboratory visit #1

3.2.3.1 Sympathetic skin responses

The degree of descending sympathetic cardiac control was assessed using sympathetic skin responses (SSR) to median nerve stimulation and deep breathing. The palmar and dorsal surfaces of both hands and feet were abraded with fine sand paper and cleaned with an alcohol swab before the application of recording electrodes. Baseline data and SSR’s were recorded simultaneously for eight seconds from both hands and feet and sampled at a band pass of three Hz to three kHz. The median nerve was stimulated (0.2 ms duration, 10–20 mA intensity) five times, with long and variable time delays (60-90s) between stimulations to prevent habituation. Participants then completed five deep breaths separated by 60-90s. Recordings at each site were obtained (Alpine/Biomed Keypoint 4, San Carlos, CA, USA) and responses were quantified based on the number of SSRs elicited at each site. Zero or one positive SSR response to stimulation/deep breathing was considered indicative of absent descending sympathetic cardiac control while two or more SSR responses to stimulation/deep breathing was considered indicative of intact sympathetic cardiac control. It has been found that individuals with SCI with two or more intact palmar SSR responses demonstrated near normal exercise heart rate responses, while those with zero or one SSR responses showed severely attenuated heart rate response to exercise.[119]

3.2.4 Graded treadmill wheeling test and physical activity monitoring period

Please refer to section 2.2.3: *Graded treadmill wheeling test* for detailed methods for the graded treadmill wheeling test and 2.2.4: *Physical activity monitoring period* for detailed methods for physical activity monitoring period.

3.2.5 Laboratory visit #2

3.2.5.1.1 Echocardiography

A transthoracic echocardiography assessment was completed in concurrence with guideline recommendations.[120] Participants transferred to an echocardiography table and positioned themselves in the left lateral decubitus position to move the heart closer to the chest wall and transducer.[121] Participants were provided with pillows and blankets to ensure their comfort and ability to maintain the left lateral decubitus position. Heart rate was recorded throughout the assessment via single-lead electrocardiogram. Following five minutes of rest, cardiac chambers were insonated form the anterior surface of the chest using a 1.5 – 4 MHz phased-array transducer on a commercially available ultrasound (Vivid 7; GE Medical, Horton, Norway). Images included five consecutive cardiac cycles recorded at the end of tidal expiration. Measures of cardiac structure were assessed from two-dimensional and M-mode images. M-mode provides a still image with high temporal resolution, with multiple frames showing the same location over time. Measures were taken both at end diastole and end systole from the parasternal long axis view. Left ventricular internal diameter (LVID) was the key structural index measured.[120] Left ventricular volumes were estimated using the Modified single-plane Simpson's method, which involves analyzing apical four-chamber views of the heart. End diastolic left ventricular volumes (EDV) and end systolic left ventricular volumes (ESV) were calculated from the summation of volumes of a series of elliptical discs.[120] Stroke volume (SV) was calculated as EDV-ESV, and was also calculated as the product of the cross-sectional area and velocity time integral of the left ventricular outflow tract. Cardiac output is the product of heart rate and SV, and ejection fraction is SV/EDV. These are global indices of systolic function.

Diastolic function outcomes were measured using pulsed wave Doppler. Early (E) and late (A) transmitral filling velocities were measured by sampling at the tips of the mitral valve leaflet with pulsed wave Doppler. Images were analyzed offline using specialized software (EchoPAC; GE Healthcare, Horton, Norway).

3.2.5.1.2 Speckle tracking echocardiography

Speckle tracking analysis of two-dimensional echocardiography images was used to measure indices of left ventricular mechanics. Briefly, speckle tracking echocardiography is an angle –independent technique that involves semi-automatic tracing of "small temporally stable and unique myocardial features" called speckles.[122] Blocks of speckles can be tracked simultaneously in multiple regions in a two-dimensional image from frame to frame. Strain, the fractional change in length of a myocardial segment expressed as a percentage, provides a regional measure of left ventricular function and was derived from the measurement of speckle displacement. Radial and circumferential strain were measured offline from parasternal short axis images of the left ventricle at the level of the mitral valve and papillary muscle, and at the level of the apex from the apical window. Longitudinal strain was measured from apical four chamber images. All indices were measured from three cardiac cycles.[122] Raw data was normalized to the percent duration of systole and diastole using cubic spline interpolation of data points (Strain Analysis Tool, custom built software) to adjust for inter- and intra- individual variability of heart rate.

3.2.6 Analyses

3.2.6.1 Cut-point calibration

Please refer to section 2.2.5.1 *Cut-point calibration* for details of the individual cut-point calibration analyses

3.2.6.2 Physical activity monitoring period

Please refer to section 2.2.5. *Comparison of individualized versus group cut-points for wheeled and non-wheeled activity'* in the methods section of Chapter 2 for details of the physical activity monitoring period analyses using individual wrist-worn accelerometer cut-points, including the breakdown of total MVPA into wheeled and non-wheeled MVPA. Please note that as group cut-points were not applied for this study these analyses were performed only using the individual cut-points.

3.2.6.3 Echocardiography and speckle tracking echocardiography

As described above, analyses of echocardiography images were performed offline using specialized computer software (EchoPAC; GE Healthcare, Horton, Norway; Strain Analysis Tool, custom built software), according to published guidelines.[120,122,123]

3.2.6.4 MVPA and cardiac indices

T-tests were performed to assess potential differences in cardiac indices between tetraplegia and paraplegia groups. Multiple linear regression was performed to determine whether there were associations between cardiac indices (dependent variable) and physical activity and injury level (explanatory variables). The breakdown of wheeled and non-wheeled MVPA was then added to the multiple linear regression model for total MVPA to assess whether this would improve any of the model outcomes

3.3 Results

3.3.1 Participant characteristics

Participant characteristics are presented in table 3.1. Age, time since injury, mass and height were similar between participants with tetraplegia and paraplegia (Table 3.1).

3.3.2 Individualized MVPA cut-points

Using regression analyses, a vector magnitude (VM-CPM) equivalent to 3 SCI METs (i.e., MVPA threshold) was calculated for each individual. The individual MVPA cut-points ranged from 6040 to 21540 VM-CPM.

3.3.3 Physical activity monitoring period

The daily mean times spent in total MVPA, wheeled MVPA, and non-wheeled MVPA during the monitoring period were similar for participants with tetraplegia and paraplegia (Table 3.1). The overall daily vector magnitude counts, representing total daily activity, were also similar between groups. The amount of time spent in non-wheeled MVPA was significantly higher than the amount of time spent in wheeled MVPA ($p<0.001$) (Table 3.1).

Table 3.1. Participant characteristics (mean ± SD), mean daily moderate-to-vigorous physical activity (MVPA) and mean total daily physical activity for participants with tetraplegia and paraplegia.

	Tetra (n=8)	**Para (n=9)**
Age (years)	42.2 ± 7.8	40.5 ± 8.8
Sex	7M/1F	6M/3F
Time Post Injury (years)	20.4 ± 10.3	23.0 ± 11.3
Height (m)	1.77 ± 0.07	1.74 ± 0.10
Mass (kg)	68.0 ± 9.2	67.9 ± 8.6
Sympathetic skin responses	0.5 ± 0.8	3.44 ± 2.2*
Total MVPA (min/day)	68.2 ± 45.2	62.8 ± 31.7
Wheeled MVPA (min/day)	19.0 ± 17.5	10.11 ± 7.8
Non-wheeled MVPA (min/day)	53.9 ± 30.3	47.6 ± 23.3
Average counts/day	2279101 ± 523424	2289085 ± 744378

*denotes $p<0.05$

3.3.4 Echocardiography

3.3.4.1 Injury level and left ventricular structure, global function and mechanics

Results for 18 participants for indices of left ventricular structure and global function are presented in table 3.2. We were unable to obtain sufficient images for speckle tracking analysis on all participants, so results reflect values of 8-12 participants (Table 3.2). There were significant between group differences in left ventricular structure, systolic function and diastolic function, whereby end diastolic volume (EDV; Table 3.2; Figure 3.1 Panel A), stroke volume (SV; Table 3.2; Figure 3.1 Panel C), cardiac output (Q; Table 3.2) and transmitral filling velocities during late diastole (A; Table 3.2) were higher in individuals with paraplegia vs. those with tetraplegia., and the ratio of early to late transmitral filling velocities during diastole (E/A) was lower in individuals paraplegia vs. those with tetraplegia (Table 3.2). There were no between group differences heart rate or left ventricular mechanics (Table 3.2).

Table 3.2. Indices of left ventricular structure, global function and mechanics in participants with tetraplegia and paraplegia.

Variable	Tetra	Para	P-value
DIMENSIONS AND VOLUMES			
IVSd (cm)	1.00 ± 0.28	0.99± 0.19	0.926
IVSs (cm)	1.31 ± 0.30	1.34 ± 0.19	0.856
LVIDd (cm)	4.63 ± 0.67	4.17 ± 0.46	0.186
LVIDs (cm)	3.37 ± 0.76	3.04 ± 0.48	0.376
LVPWd (cm)	0.90 ± 0.23	0.91 ± 0.23	0.911
LVPWs (cm)	1.30 ± 0.34	1.29 ± 0.27	0.915
End diastolic volume (ml)	90 ± 19	109 ± 21.6	**0.07**
End systolic volume (ml)	42 ± 14	48 ± 15	0.427
SYSTOLIC FUNCTION			
Left Ventricular Outflow Tract			
SV (ml)	56 ± 13	72 ± 12	**0.023**
HR (bpm)	59 ± 9	66 ± 13	0.273
Q (L/min)	3.17 ± 0.70	4.74 ± 1.16	**0.008**
DIASTOLIC FUNCTION			
E ($cm{\cdot}s^{-1}$)	0.75±0.09	0.73±0.16	0.768
A ($cm{\cdot}s^{-1}$)	0.31±0.05	0.51±0.12	**0.001**
E/A	2.53±0.51	1.56±0.64	**0.005**
MECHANICS			
εl min(%)	1.40 ± 0.55	1.91 ± 0.49	0.493
εl peak (%)	-15.71 ± 3.63	-16.27 ± 2.25	0.758
εr peak (%)			
Basal level	29.64±5.76	27.49±11.22	0.769
Mid level	30.99 ± 15.92	33.75±7.53	0.724
Apical level	26.34± 9.02	16.76 ± 2.31	0.207
εc peak (%)			
Basal level	2.12±2.29	4.79±5.40	0.383
Mid level	1.90±2.15	3.88±3.44	0.400
Apical level	3.01±2.60	1.19±0.92	0.390
εc min (%)			
Basal level	-10.79±2.81	-14.33±5.12	0.247
Mid level	-9.15±4.45	-12.65±4.71	0.321
Apical level	-14.20±6.16	-18.41±5.21	0.424

Data are mean ± SD. Abbreviations: IVSd, interventricular septum during diastole; IVSs, interventricular septum during systole; LVIDd, left ventricular internal diameter during diastole; LVIDs, left ventricular internal diameter during systole; LVPWd, left ventricular posterior wall during diastole, LVPWs, left ventricular posterior wall during systole; EF, ejection fraction; SV, stroke volume; HR, heart rate; Q, cardiac output; E, transmitral filling velocities during early diastole, A, transmitral filling velocities during late diastole; ε, strain; l, longitudinal; r, radial; c, circumferential. Bolded values in P-value column indicate significant between-group differences.

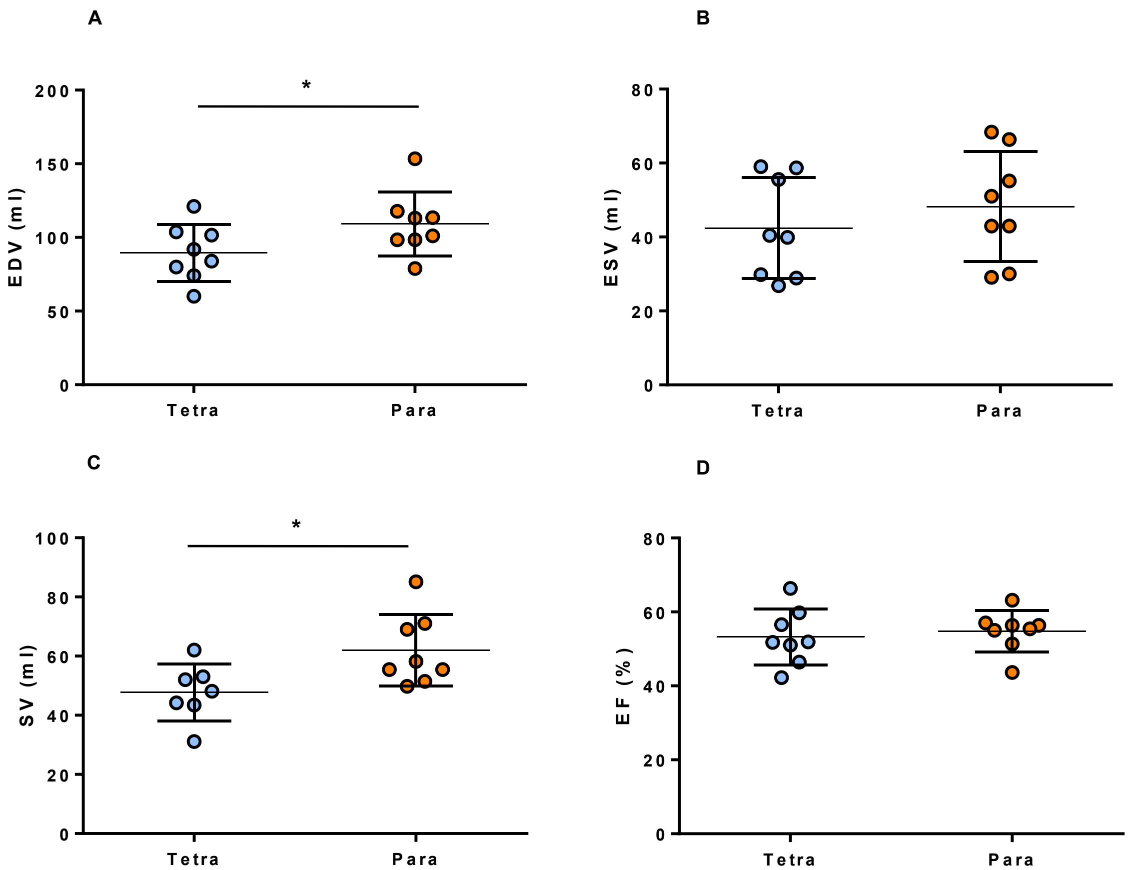

Figure 3.1. End diastolic volume (EDV; Panel A) and stroke volume (SV; Panel C) were lower in participants with tetraplegia (tetra) vs. participants with paraplegia (para) (EDV: p=0.074 and SV: p=0.023). End systolic volume (ESV; Panel B) and ejection fraction (EF; Panel D) were not different between groups. Each dot represents one participant; the middle horizontal bars show the group means and the vertical bars show the standard deviations.

3.3.4.2 MVPA and left ventricular structure and global function

Multiple linear regression revealed associations between total MVPA and end diastolic volume (EDV) and end systolic volume (ESV) (both p<0.01 independent of injury level, whereby those with the highest MVPA had the highest EDV and ESV (Table 3.3; Figure 3.2 panels A and B). Stroke volume (SV) was associated with both daily MVPA (Figure 3.2 panel B) and level of injury (both p<0.05), whereby those with the lowest MVPA and highest injuries exhibited the lowest SV. Adding the breakdown of wheeled and non-wheeled MVPA to total MVPA did not improve any of the model outcomes. There were no associations between diastolic indices and MVPA. Overall daily vector magnitude counts, reflecting total daily activity, were not associated with any cardiac indices.

Table 3.3. Multiple linear regression results and significance relating moderate-to-vigorous physical activity (MVPA) to cardiac indices.

Outcome	**Beta coefficient (SE)**	**P-value**
Total MVPA		
EDV		
MVPA	0.46 (0.77)	**0.000**
Injury level	20.64 (6.62)	**0.008**
ESV		
MVPA	0.28 (0.06)	**0.000**
Injury level	7.42 (4.79)	0.145
SV		
MVPA	0.18 (0.05)	**0.005**
Injury level	13.96 (4.62)	**0.010**

Abbreviations: MVPA: moderate-to-vigorous physical activity; EDV: end diastolic volume; ESV: end systolic volume; SV: stroke volume. Bolded values in P-value column indicate significant associations.

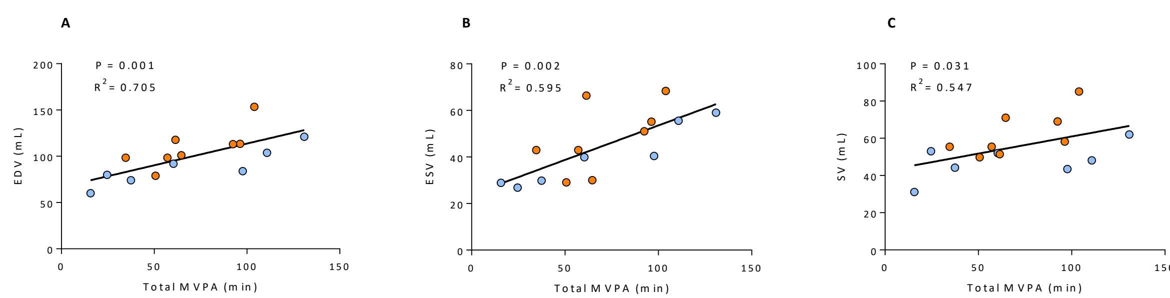

Figure 4.2. Multiple linear regression revealed associations between total MVPA and end diastolic volume (EDV; Panel A), end systolic volume (ESV; Panel B) and stroke volume (SV; Panel C) independent of injury level, whereby those with the highest MVPA had the highest EDV, ESV and SV. Each dot represents one participant, with individuals with tetraplegia in blue and paraplegia in orange. R^2 is reported for the group model while P is reported for MVPA.

3.3.4.3 MVPA and left ventricular mechanics

Indices of left ventricular mechanics are presented in table 2. There were no differences in left ventricular mechanics between participants with tetraplegia and paraplegia. Total MVPA, wheeled MVPA and non-wheeled MVPA were not associated with any indices of left ventricular mechanics.

3.4 Discussion

We found that level of injury and total MVPA were both independently associated with indices of left ventricular global systolic function, whereby those with paraplegia and those who had the highest MVPA exhibited better global systolic function. In contrast to our findings on global systolic function, we found no associations between MVPA and indices of global diastolic function or measures of left ventricular mechanics. There were also no associations between total physical activity and any cardiac indices. These findings indicate that higher intensity physical activity is important for optimal global systolic function in individuals with SCI.

3.4.1 Global systolic function was attenuated in tetraplegia compared to paraplegia

Indices of left ventricular structure and global systolic function were reduced in individuals with tetraplegia versus those with paraplegia. We found lower SV and cardiac output in the individuals with tetraplegia compared to those with paraplegia. End diastolic volume (EDV) was lower in tetraplegia but end systolic volume (ESV) was similar between groups. The difference between EDV and ESV is equal to SV, thus lower EDV resulted in lower SV and therefore lower cardiac output in tetraplegia. The reductions in EDV were not attributable to differences in left ventricular size or geometry between tetraplegia and paraplegia because short axis left ventricular internal diameters during diastole (LVIDd), left ventricular long axis lengths, and sphericity (length/LVIDd) were similar between groups. Thus, the reduced EDV in tetraplegia is indicative of reduced venous return in tetraplegia.

Reduced venous return following SCI,[39] results from decreased blood volume,[36] loss of skeletal and respiratory muscle pumps,[37,38] as well as reduced vascular tone and lack of vasoconstriction below the level of injury.[35,40] This consequential decrease in left ventricular filling, which decreases the volumetric output of the left ventricle in individuals with tetraplegia, has been observed in numerous studies.[42,45,53,55]

We found no differences in ejection fraction between individuals with paraplegia and tetraplegia in the present study. This suggests that while individuals with paraplegia had higher SV, it is only attributable to higher EDV and not higher contractility in paraplegia versus tetraplegia, a notion further supported by the observed similar left ventricular mechanics in tetraplegia and paraplegia, discussed below. However, it could be that individuals with tetraplegia do have impaired contractility, but in the face of decreased afterload are able to maintain ejection fraction.[2]

Ejection fraction has been reported as reduced[53] or unchanged[33,45,55] in individuals with tetraplegia. Comparisons of ejection fraction in a pooled sample of individuals with tetraplegia and paraplegia to able bodied individuals revealed no differences in ejection fraction.[54] Similar ejection fractions have also been found in comparisons of individuals with paraplegia and able bodied individuals.[49] Our findings of similar ejection fraction between tetraplegia and paraplegia are thus not unusual.

We found that E/A ratio, a measure of global diastolic function, was lower in individuals with paraplegia versus tetraplegia, however this was solely due to greater late transmitral filling velocity (A) in the paraplegic group. The increased late transmitral filling velocity seen here may potentially be a result of higher left ventricular compliance in individuals with paraplegia, meaning that more blood can enter the left ventricle for the same atrial contraction. Our findings are in contrast with previous reports of similar ratios of early to late filing (E/A) between individuals without SCI and individuals with tetraplegia,[33,43] individuals with paraplegia,[47] and pooled samples of individuals with tetraplegia and paraplegia.[45,46] Currie et al. (2016) found no differences in indices of global diastolic function between Paralympic athletes with tetraplegia versus Paralympic athletes with paraplegia.[55] West (2012) also found no differences in filling velocities in a comparison of highly trained athletes with tetraplegia to recreationally active individuals without SCI.[53] In contrast, decreased E/A has been found in pooled samples of individuals with tetraplegia and paraplegia compared to individuals without SCI. Further investigation is required to understand the impact of injury level on diastolic function following SCI.

3.4.2 Left ventricular mechanics were similar in tetraplegia and paraplegia

There were no differences in any indices of left ventricular mechanics between individuals with tetraplegia and paraplegia in this study. This suggests that the observed reductions in SV may be due to impaired loading rather than inherent left ventricular dysfunction. This is in contrast with results of the only previous study to examine injury level differences in left ventricular mechanics, which found that indices of systolic and diastolic left ventricular mechanics were maintained in Paralympic athletes with tetraplegia but reduced in Paralympic athletes with paraplegia, despite reduced global systolic dysfunction in tetraplegia.[55] The authors propose that the absence of association between their findings of reduced global systolic dysfunction and left ventricular mechanics suggest that reduced SV in SCI is attributable to impaired loading rather than inherent left ventricular dysfunction.[55] These metrics are, however, all dependent on load and therefore cannot rule out inherent left ventricular function. In fact, pre-clinical work has shown that load-independent function is impaired in high-level experimental SCI, and cannot be restored with exercise.[124]

3.4.3 Moderate-to-vigorous physical activity was independently associated with indices of global systolic function

The main findings of this study were that MVPA was associated with indices of left ventricular structure and global function, independent of level of injury. Interestingly, most of the MVPA completed by participants in this study was non-wheeled activity. The multiple linear regression model revealed that MVPA was a stronger predictor of cardiac function than level of injury. This suggests that MVPA may be more indicative of cardiac function than injury level in individuals with SCI.

Individuals with higher MVPA had higher EDV and SV. ESV was increased with higher MVPA, but to a lesser extent than EDV, and there were no associations between MVPA and left ventricular internal diameters in the short axis. Thus, increased SV seen here is likely attributable to increased preload, EDV and SV, secondary to increased venous return. Recent work has found similar SV in trained versus untrained males with tetraplegia.[45,125] Athletes with tetraplegia have also shown reduced SV in comparison to able bodied persons.[53,125] In individuals with paraplegia, however, there is evidence of both lower[45,49] and similar[51] SV in sedentary individuals compared to active individuals with paraplegia. Active individuals with paraplegia have also exhibited SV similar to able bodied individuals.[49] Given that the evidence to date suggests that physical activity may improve global systolic function in individuals with paraplegia but not tetraplegia, it is noteworthy that MVPA was associated with EDV, ESV and SV independent of level of injury in this study. Thirteen of 18 people in this study had injuries above the level that would disrupt control of splanchnic vasculature, therefore, in almost all individuals, venous return from the splanchnic and lower limb area would be impaired. Previous work has shown that by encouraging venous return to the heart via exercise, volumetric indices of the heart can be restored.[56] Therefore, it is unsurprising that in our study, where the disruption in left ventricular loading was relatively homogenous, that MVPA was a stronger predictor of global systolic function than level of injury.

3.4.4 Moderate-to-vigorous physical activity was not associated with indices of diastolic function

There were no associations between MVPA and indices of diastolic function. Diastolic filling is dependent on diastolic suction during early transmitral filling, left ventricular compliance, and atrial function during late transmitral filling.[126] That we did not find any differences indicates that physical activity did not improve any of these components enough to alter resting diastolic function. This is in line with previous findings of similar transmitral filling velocities between trained and untrained individuals with paraplegia,[47] between wheelchair athletes with paraplegia, long distance runners and able-bodied control participants,[50] and between active and sedentary individuals with tetraplegia and paraplegia, either in a pooled sample or within tetraplegia and paraplegia subgroups.[45]

3.4.5 Moderate-to-vigorous physical activity was not associated with indices of left ventricular mechanics

Speckle tracking echocardiography is a clinically-relevant angle-of-insonation independent measure of left ventricular mechanics, thought to be a more sensitive indicator of impending global cardiac dysfunction.[127–129] That we found no associations between MVPA and mechanics further supports the notion that the better global systolic function seen in individuals with SCI who are more active may be attributable solely to increased volume loading of the heart and is not indicative of improved function of the myocardium *per se*. This is in line with a recent pre-clinical investigation where our laboratory documented diminished pressure generating capacity (end systolic pressure; Pes, and the maximal slope of left ventricular systolic pressure increment; dP/dtmax) and load independent contractile function (slope of the end systolic pressure volume relationship (end-systolic elastance; Ees), preload recruitable stroke work; PRSW, and the slope of the dP/dtmax end-diastolic volume relationship; dP/dtmax-EDV) of the heart following T2 level SCI in rats.[124] Passive hind-limb cycling reversed SCI induced reductions in SV, but was unable to normalize the pressure generating capacity or load independent contractile function of the heart. The pressure generating capacity and contractile function of the heart were normalized only by administration of the sympathomimetic dobutamine, which acts directly on cardiac beta-receptors. These results indicate that cardiac dysfunction following SCI is likely a result of left ventricular unloading and disrupted descending control of the sympathetic innervation of the heart, and that physical activity may reverse only the unloading induced declines in global systolic function.[124] Thus, our findings in the present study of independent associations between MVPA and global systolic function despite the absence of associations between MVPA and left ventricular mechanics indicate daily habitual MVPA has the capacity to improve global systolic cardiac function through volume loading the heart, but MVPA does not improve the function of the myocardium *per se*.

3.4.6 Limitations

As addressed in section 2.4.3 *Study limitations*, there are some considerations when using cut-points derived from a treadmill based test to classify intensity of physical activity during non-wheeling activities of daily life, non-wheeling exercise activities, wheeling uphill and on different surfaces. Specifically, the intensity of these activities may be misrepresented, thus we suggested wrist-worn accelerometry and wheelchair spoke accelerometry as measures of physical activity should be combined with additional measures for a more complete picture of the types and contexts of physical activity. It is also possible that the use of the SCI MET value of 2.7 ml/kg/min may have resulted in an over- or under- estimation of physical in some participants. It is possible the left ventricular mechanics analyses were underpowered as the image quality was sufficient to perform speckle tracking analyses in only half of the participants. Thus, there may be undetected differences between individuals with paraplegia and those with tetraplegia, or an undetected relationship between left ventricular mechanics and MVPA.

3.5 Conclusion

MVPA was associated with global systolic cardiac function independent of injury level, however there were no associations between total activity and any cardiac indices These results suggest individuals with SCI of all injury levels should participate in MVPA for optimal cardiac function.

Chapter 4: Barriers, facilitators and meanings related to physical activity participation during the physical activity monitoring period

4.1 Introduction

Individuals with SCI are at greatly increased risk and odds of heart disease.[4,113] In fact, cardiovascular disease is the number one cause of death in this population.[113] Cardiac dysfunction is exhibited in people with SCI, characterized by left ventricular atrophy[42,43] and impaired systolic function,[42,53] attributable to multiple mechanisms discussed in the previous chapter. In short, these factors result in unloading of the left ventricle that is exacerbated by immobility.[118]

Our results discussed in chapter 3 suggest that participation in moderate-vigorous physical activity (MVPA) is important for optimal cardiac function in individuals with SCI. There are, however, numerous barriers to physical activity participation in this population. Factors impacting physical activity participation are interacting and complex, as shown by work identifying several categories of barriers and facilitators, such as accessibility of the physical environment, economic and other resources, equipment, knowledge, education and information, societal attitudes, emotional and psychological barriers.[64,66,68,69] Here, we had a unique opportunity to contribute to the literature on barriers and facilitators using a combination of quantitative and qualitative methods. This study is informed by the social ecological model of health promotion behavior applied to physical activity participation, described in section 1.6: *The social ecological model to understand factors impacting physical activity participation*. Briefly, the social ecological model examines multiple interdependent levels of influence related to health promotion behaviour. These levels include: intrapersonal, interpersonal, institutional, community and policy. The objective of this study was therefore to illuminate wrist-worn accelerometry derived physical activity data from a six-day monitoring period using qualitative data on the barriers and facilitators to physical activity during that time.

4.2 Methods

4.2.1 Study design

The study was intended to be exploratory in nature, with the unique added element of qualitative interviews to accelerometry derived physical activity monitoring data. I hoped to gain insight into the physical activity experiences of participants, provide context to the monitoring data and explore factors promoting or inhibiting participants' physical activity during that time. To accomplish this, I used semi structured in depth interviewing to obtain personal accounts of the barriers and facilitators experienced during a physical activity monitoring period. The physical activity monitoring period consisted of six or seven days of wearing a wrist and spoke accelerometer. Details of the monitoring period protocol and analyses can be found in chapter 2. The interviews took place within a week of the monitoring period so that participants would more easily be able to remember details from the monitoring period, except for one participant whose interview was a few days later due to scheduling conflicts. Interviews were conducted at ICORD and lasted on average 47 minutes (range 24-75 minutes per interview, total of 4 hours).

The interview first focused on the participant's experiences during the physical activity - monitoring period, and reflections on physical activity during that time. Specific probes directed the conversation to barriers and facilitators to participation. Next, I introduced the participant's monitoring data, including specific days and time periods during which they were particularly active or inactive, with the aim of sparking further reflections and impressions of the data. Please refer to appendix A for the interview schedule.

The accelerometry data on physical activity participation was used as a probe to help facilitate additional reflection on the part of participants about their experiences of physical activity and the barriers and facilitators they encountered during the monitoring period. The interview schedule was not limited solely to a discussion of physical activity during the monitoring period to encourage participants to express their thoughts and views related to physical activity that were most relevant and important to them. This method was intended to illuminate our findings on their minutes of daily physical activity participation by exploring the "what/how/why" information the accelerometry data could not provide.

4.2.2 Sample

Data collection for this study was completed between July and September of 2016. Five participants completed this study. They also completed the physical activity monitoring and cardiac function assessment studies presented in chapter 2 in this time frame. These participants were the only five to complete the physical activity monitoring and cardiac function assessment studies during this time frame. Thus, all participants that completed the first two studies since the addition of the interview component also participated in this study.

Participant demographic characteristics are presented in Table 4.1. All participants self-identified as male, heterosexual and had no children. There was a range of age, place of birth, marital status, level of education and annual income (Table 4.1). Three participants had cervical SCI while two had low thoracic SCI. Mean daily MVPA ranged from 24.6 minutes to 96.3 minutes, with a group mean daily MVPA of 62.2 minutes. On average, 80% of MVPA completed by the sample comprised of non-wheeled activities. The three participants with cervical SCI tended to be less active than the two participants with thoracic SCI, as they completed 60, 38 and 25 minutes of MVPA compared to 96 and 92 minutes of MVPA completed by those with thoracic SCI.

Table 4.1. Socio-demographic characteristics of participants.

Age	**Frequency**
30-40	1
40-50	1
50-60	3
Place of Birth	
Canada	3
Europe	1
Asia	1
Marital Status	
Married or common Law	2
Divorced or separated	2
Never married	1
Level of Education	
High school	2
College/university degree	2
Graduate degree	1
Annual Income	
Less than $15 000	2
$16 000 - $35 000	2
More than $155 000	1

All participants self-identified as male, heterosexual, and had no children.

4.2.3 Analyses

The interviews were digitally recorded and transcribed verbatim. Codes and themes were derived from the interview schedule. A senior researcher experienced in qualitative research methods read two of the five transcripts independently and together we agreed upon broad codes and sub codes. The broad codes included barriers, facilitators and meanings. Barriers to physical activity participation included things that made it difficult or impossible for participants to engage in physical activity. Facilitators to physical activity participation encompassed things that made it easier or more possible for participants to be physically active. Meanings included reasons for doing physical activity, activities that participants viewed as constituting physical activity and general impressions of the physical activity monitoring period data.

The sub codes within barriers included access to physical activity and bodily barriers, while the sub codes for facilitators included access and structure. The sub codes for meanings included reasons for doing physical activity, activities that participants viewed as constituting physical activity and general impressions of the physical activity monitoring period data. We generally followed the six-phase approach to thematic analysis outlined by Braun and Clarke (2012). Briefly, these six phases included familiarization with the data, generation of initial codes, identification of themes, review of potential themes, definition and naming of themes, and writing the report.[130] The data analyses and writing processes were not linear, but rather the data was continually revisited to hone analyses and inform writing.

4.2.4 Reflexivity

It must be noted that I am a young, white, able-bodied woman of privilege, from a university educated family, completing a graduate degree in a city. I am highly physically active and generally consider physical activity to be a positive influence both in my life and for others. The semi structured interview was conducted at ICORD during each participant's third laboratory visit, by which time my personal views on physical activity were likely apparent. All participants were physically active in this study, which I had in common with them, but I was different from the participants in terms of age, socio-economic status and being able bodied. These factors increased my status as an outsider to participants, unavoidably influenced both my approach to data collection and interpretation and likely influenced the responses of the participants in this study. There was potential for gender and power dynamics of the interview process to impact the participants and the data generated. Previous work has identified gender and age as key factors determining interactions, disclosure and emotional expression during qualitative research interviews.[131] For example, it was found that when women interviewed men with mobility impairments, the interviewees avoided discussing emotion, however, the women interviewers were more easily able to encourage the men to open up about personal matters.[131] Thus, I believe that the differences between myself and the participants in this study positioned me as someone they felt comfortable sharing their experiences with.

4.3 Results

The barriers discussed related to issues of access and bodily barriers, while facilitators centered around access and structure. Multiple reasons for doing physical activity were apparent, including for enjoyment and to optimize function. Participants' also demonstrated a range of impressions of their physical activity data.

4.3.1 Barriers

The barriers discussed by participants centered around two subthemes, including access to physical activity and bodily barriers.

4.3.1.1 Access barriers

Discussed by four of the five participants, the issue of access included concerns about distance or terrain, gym environments, cost, and requiring someone else to do physical activity with. To begin, one participant noted that distance to places he needed to go made it difficult for him to be physically active, as he explained:

> Sometimes I drive … the only time I'll take sky train [is] if I'm going from point A to point B, like if I'm going from [work] to the … sky train station. Or if I'm going here … I'll take the train. But usually if I've got things to do, or if it's kind of off the beaten path I'll drive, which is probably not as good for me. It's a time thing. I don't want to be standing around…Absolutely, distance does play a factor (PA019).

This participant was less active than he may have otherwise been because he drove places that were not conveniently accessible by a combination of transit and wheeling. Not only was distance a factor impacting physical activity in this study, but the terrain/elevation of that distance was key in determining one participant's mode of transportation. PA021 explained that he decided to bus to ICORD even though it was not too far away, because it would be "in [his] range if it wasn't so many hills" (PA021). This participant was less active because he had to take the bus because it was too hilly to wheel. In addition to limiting wheeled physical activity for transportation, the distance to accessible gyms also arose as a factor impacting physical activity participation at the gym. For example, one participant explained:

> Well now that we're talking barriers, let me be clear, I think the lack of options for me … if the PARC was next door I might go to it in the morning, right. But because it's up here at 10th, it's just far enough away that I get as much exercise wheeling here as I would being here (PA022).

The inconvenience of the distance from this participant's home to a gym with adapted equipment limited his use of the centre. In addition to the distance to gyms, the layout of gym space was also a limitation to physical activity participation for one participant, as articulated by PA019 who explained:

> So the gym I work out at is … small. It's cramped. It's crowded…If you want to talk inclusion of a person with a disability, very few community centers, I've been to a lot of them... there are very few that can boast that. There's very few equipment that's adaptable. And I know that we are a small segment of the population that's using the gym, most people in the gyms are able bodied people, so cost wise they're the ones using the machines. So if there's one thing that I encounter almost every time, you have to work around that. You learn to just work around other people, lack of space, using dumbbells that are not in your reach. You know, sometimes I have to ask people to grab weights for me because it's a funny little gym. They got their bench press. They've got their plates positioned in front of the bench press, so sometimes it's hard for me to get in there to pull the plates off...for complete accessibility. Yeah, that would be an issue for sure.

PA019 described a well-established work-out routine and ways to work around barriers, yet was still limited by small, cramped space at the gym and lack of adaptable equipment.

Cost was also a key factor in determining access to physical activity for participants. Participants that were employed or had more financial support seemed to have more access to both structured physical activity programs as well as less structured activities like outings and trips, or could afford specialized equipment, while for others the cost of physical activity programs could be prohibitive. One participant who was unemployed and used to be involved in sport said "I don't know what to do. I keep thinking to get back to the rowing, but…it's money that's a problem" (PA023).

Four participants also described lack of social support as a barrier to physical activity. For example, PA023 described how having a limited social network impacted his physical activity, as he stated:

> I used to be pretty active. I thought it's because I'm getting old or something like that, but no it's hard, it dragged me down you know. Now I'm back. I just have to make phone calls and get ahold of friends.

PA023 used to go on trips and participate in physical activity with his friends, but lost touch with many of those friends. Being out of touch with his social network impacted this participant's physical activity participation. In addition to the impact of lacking a social network for company during physical activity, four participants faced the barrier of requiring assistance to do preferred physical activities. This was articulated by PA023 who explained that to participate in his preferred activity of rowing, he needed: "Another safety boat…. Apparently if I tip over or something like that…but… there's nobody that would go with me. After a month of going there by myself and going to the gym by myself, I quit". Similarly, PA021 enjoyed kayaking but his participation could also be limited because he required assistance for safety. PA019 had to adjust his workout at the gym when he did not have someone to assist him, and PA022 needed assistance to attach equipment to do his preferred activity. Although a lack of assistance did not stop participants from being active, it limited their participation in certain preferred activities because of safety concerns.

4.3.1.2 Bodily barriers

Identified by two participants, bodily barriers included finite energy, injury and soreness. Participants reported having only a finite amount of energy to spend in a day and thus having to make sometimes difficult decisions about how to spend that energy. For example, if they had to wheel for transportation more than usual, this decreased the energy they had for physical activities at the gym. PA019 explained: “I find if I’m busier, the training is reduced a bit, or altered a bit”. Related to the issue of having finite energy was the impact of bodily soreness and/or injury on physical activity participation. PA021 explained that he was “Always sore, you can’t exercise when you’re sore….it’s nothing compared to what I usually do. Which I’m trying to slow down. I hate going to bed sore and waking up sore”. This participant was forced to slow down due to injury and soreness, preventing him from being as active as he may have liked.

4.3.2 Facilitators

Several factors that supported participants in being physically active, making it easier or possible, were apparent in this study. The facilitators identified by participants included access and structure.

4.3.3 Access facilitators

Living in an environment with lots of opportunities for physical activity was a key facilitator to participation for two participants. These opportunities included the incorporation of physical activity into daily activities such as errands, as explained by PA020: “That mall is across the street. The grocery store, all that kind of stuff, everything is around there. So, I’d rather wheel than just get in my car and just drive”. In addition to promoting the incorporation of physical activity into daily life, living in a central location also made it easier for two participants to go wheeling for the sake of physical activity itself. This was expressed by PA022, who explained:

> Where I live is a factor. You know, if I was living where I used to live … I probably would not have wheeled nearly as much because … I don’t have the nice waterfront to wheel along, and it’s an inconvenient spot to exercise. And when I lived there I did notice that I exercised less. I lived there for 4 years, and I said you know this isn’t good for my physical health. Part of my decision to move back downtown was to get somewhere where I could have easier access to flat and walking trails.

This participant lived in an ideal central location with ample opportunity for physical activity. He was also unique in that his financial situation allowed him to decide where to live to maximize his physical activity. Access to low cost gyms such as PARC was another facilitator for participants.

Finally, warm weather was identified as a factor facilitating physical activity for two participants perhaps in part because the physical activity monitoring period and interviews were conducted in the summer months. PA022 said “Last week happened to be a great week weather wise, so I did a lot of walking”. PA021 explained: “The heat’s actually good for the shoulder [injury]” (PA021). The warm weather facilitated physical activity for this participant by attenuating the physical soreness he experienced due to injury.

4.3.4 Structural facilitators

Different forms of structure also made it easier or possible for all five participants to be physically active. This was expressed by PA021, who explained that a key form of structure facilitating physical activity included plans with his family:

> I get a call from my sister, and next thing I know … I'm on a trip going here, doing this...I usually…plan things out…You don't have control if you don't plan things...over the situation where you're going, if it's accessible or not.

Structured plans and social support for activities made it easier for this participant to maximize activity and circumvent access barriers. For example, it allowed him to determine ahead of time where he would have access to bathrooms on a camping trip. For two participants, structure as a facilitator to physical activity was expressed in the form of daily routine. This was expressed by PA019, who explained:

> My morning routines are pretty similar day to day. I get up in the morning, … do a couple hours of work on the computer, I have breakfast, shave. Then I go and work out, and I am pretty consistent with my workouts. I am not a late afternoon guy. If I wait … there is a good chance I won't work out, so I like to get it done first thing in the morning at 8-9 latest.

This participant scheduled his day to maximize the likelihood that he would do physical activity, based on the knowledge and self-awareness that he was less likely to work out if he left it until later in the day. Similarly, PA022's physical activity was also facilitated by daily routine. He described his daily routine of working a few hours in the morning and then going outside to wheel. PA022 explained: "My routine tends to be if it's nice weather outside, I'll go out for a couple hours every day and exercise". For PA020, daily physical activity participation largely depended on the number of errands he had to do on any given day. He said, "I think it all boils down [to] what I have to do each day or each week". Having tasks to accomplish provided structure and facilitated physical activity for this participant. Additionally, structure came in the form of coaching for PA023. He had previously been involved in rowing and explained that he "Had a very very tough coach, she was awesome…She would kick my ass if I didn't do what I was supposed to do…. She was awesome, she was tough". Unfortunately, after he returned to rowing after an injury, the club had been reorganized and the coach had left, so he lost the activity promoting structure and social support of organized sport.

4.3.5 Meanings

4.3.5.1 Reasons for doing physical activity

Multiple meanings behind why participants did physical activity were evident in the transcripts. The main reasons for doing physical activity were because it felt good and to optimize function.

4.3.5.1.1 It feels good

For four participants, it felt good to do physical activity. This was described by PA019, who explained: “I like doing it. I like the way you feel, I like being strong, I like it all”. In addition to enjoying the physical feeling, participants also liked the challenge of physical activity, as expressed by PA021, who said “Well I like the working out part. I enjoy pushing myself”. Similarly, PA019 described the feeling after a workout, explaining: “I was taxed. I was tired. It was intense, it was good". PA022 said, “I genuinely love [physical activity]. It’s a great way to de-stress”. Physical activity felt good for participants both during and after the activity, physically and psychologically, providing a sense of accomplishment. PA023 enjoyed physical activity socially, as evidenced by his statement: “It was fun going to the store with the guys”. PA021 also enjoyed physical activity because it was a way for him to be out in nature, as he described: “Even when it’s cold out, I was out there pushing. It was nice just to get out of the house. Even if it’s raining. I like being out in nature”. Enjoyment of physical activity was key in most participants’ reasons for doing activity.

4.3.5.1.2 For function

Discussed by three participants, a second key reason for doing physical activity was to optimize function, including health and independence. This was articulated by PA021, who explained how he used to have more functional issues before he was active:

> When I first got here, I couldn't push for long. I was overweight too...my shoulders were always sore, my ribs. Now on occasion I will overdo it, but as long as I take one day off … I can actually sleep now I have more exercise. When I first got here I couldn't sleep.

Physical activity helped PA021 lose weight, decrease soreness and improve his sleep. Physical activity improved his function and served to attenuate bodily barriers to participation. Similarly, PA022 also participated in physical activity for function, as he explained:

> I'm in a groove where I wheel an hour to two hours, five to seven days a week. And that…has kept me healthy, and [has] kept me out of an electric chair for as long as possible ….. Part of the reason that I exercise so much is because the more weight I have, the harder it is for me to transfer, and then the harder it is for me to be independent. The key for me is, because I need an attendant care …during the day, I try and minimize the amount of time that is.

Physical activity helped PA022 maintain his health and weight, increased his independence and minimized his need for assistance. Additionally, PA019 described physical activity as a way to maintain function with increasing age. PA019 explained,

> If you're a person in a wheelchair and you're not working out, your quality of life is going to suffer. Your longevity is going to suffer. So…if you want to be a 60-year-old person with a disability, you better be involved in some physical activity. If you want quality of life when you get to 60 or older.

There was a highly positive view of the functional benefits of physical activity represented in this sample.

4.3.5.2 What physical activity is and impressions of monitoring data

Participants were shown the daily and hourly breakdown of their wrist accelerometer physical activity data, but were not shown the breakdown of this activity into wheeled and non-wheeled activity as the spoke accelerometry analyses were not completed at the time of the interviews. Participants' impressions of their data from the physical activity monitoring period varied, revealing a range of opinions on the accuracy of the data and their own perceptions of their physical activity participation.

PA019 completed an average of 60.3 minutes of MVPA per day during the monitoring period, including 8.9 minutes wheeled and 51.4 non-wheeled. When he was shown the daily and hourly breakdown of his wrist accelerometer data, he generally agreed that it accurately portrayed his activity during the monitoring period. For example, after going through data from one of the monitoring period days, he said: "Yep it's bang on. That's exactly what I did that day". PA019, when asked about physical activity, largely focused on his weight training workouts, but also pointed out that habitual wheeling for transportation was "Cardio for sure". He commented that in terms of physical activity, the monitoring period "Was a good week. It truly was…I had one really good push.... it was a good week. It was pretty busy. I had a couple meetings downtown". PA019 discussed both exercise in the gym and habitual wheeling for transportation as physical activity.

PA020 completed an average of 37.5 minutes of MVPA per day during the monitoring period, including 8.4 minutes wheeled and 29.1 non-wheeled. He was unable to comment whether his physical activity data seemed accurate because it was difficult for him to remember enough to compare details. When asked about his physical activity, his focus was on wheeling for transportation and daily activities. For example, he said:

> I was pretty active on this day. I did a lot of just driving and going to the park and stuff like that. Wheel around and ... this is … normal for me on these days…What I would do, I would be out all the time, driving around going places...Usually, I'm out wheeling around … getting food or groceries or doing something, just wheeling around the neighborhood.

PA020 felt that the monitoring period was representative of a normal week in terms of physical activity, and offered that on a personal scale of one to ten representing activity level, his activity during the monitoring period rated eight or nine.

PA021 completed 96.3 minutes of total mean daily MVPA, 24.8 of which was wheeled and 71.5 that was non-wheeled. PA021 described his data from the physical activity monitoring period as "Fairly accurate", however there was some incongruence between his perception of activity intensity and the intensity determined through accelerometry analyses. There was some activity that was classified as light that PA021 thought would be more intense. He said, "One of the things I think is hard is my body doesn't seem to register it that way... I think it would be more energy. The times don't match up". Based on this, he concluded "I'm probably in better shape than I think I am... I didn't think I would be…I'd be huffing and puffing". His view of physical activity intensity seems to have changed from participating in this study. He revealed that it encouraged him to think:

> More about things I do every day. I don't think it's exercise but it is. Just getting up and getting something to eat, that's work... But I don't think of it as work. But for some people it would be a lot of work.

In comparison to other weeks, PA021 felt he was less active than normal, explaining: "It's nothing compared to what I usually do". He also said, however, "Knowing I had to do something for part of this [study], so I tried to be fairly active, not just laying around", implying he was more active than normal during the monitoring period, so it is unclear how his activity level would have compared to a usual week.

PA022 completed an average 24.6 minutes of MVPA daily, including 4.9 minutes wheeled and 19.7 minutes non-wheeled during the monitoring period. He tended to disagree with the accelerometry data in terms of the intensity of his physical activity. When asked about physical activity, PA022 reported mostly wheeled activity, much of which was classified as light intensity. PA022 believed that the intensity had been misclassified and that his wheeled activity was of moderate intensity. He explained:

> Well for me, the wheeling is more moderate than light. I know maybe because I do slow strokes, I don't know what it is but…Like when I wheeled from my place to Granville Island, I would say that would be moderate. And with a couple [minutes of] heavy, but heavy for like one minute going up the hill and stuff like that. So, when I look at this, and between eleven and twelve, which is when I did constant wheeling, it breaks it down. I guess they call that light, right?

There was additional physical activity that was classified as light that PA022 believed was sedentary time. He said, "Actually that would be sedentary in my mind, but again I'm not sure why". In contrast to PA021, who believed the data and whose perceptions of physical activity and of his own fitness consequently adjusted, PA022 rejected the data, saying: "Let's just call your algorithm a work in progress". PA023 was also surprised by his physical activity data, because he did not think he was very active while the accelerometer measured 90 minutes of mean daily MVPA. He described packing, which was classified by the accelerometry analyses as a combination of light and moderate to vigorous intensity activity, and involved: "Getting in the car, get out, go downstairs, up the ramp, down the ramp, and up, in the van, go back", as "Not something hard. It's not something that gets me like oh my gosh I'm so tired". He further explained: "Well that's a typical day. For me, being active means training or go wheeling a lot or … when I'm actually exhausted. When I'm huffing, and puffing, you know. I guess people think differently about what … counts as activity". As PA023 summarized nicely, it was evident that participants thought differently about counts as activity, and the intensity of that activity.

4.3.5.3 What being active says about an individual

Participants also discussed their views on what it means for other people with SCI to be active or inactive. Three of five participants also indicated that they believed that it was largely up to the individual to be active, suggesting or even explicitly stating that being active or not is simply part of a person's character. For example, PA022 explained that: "I think that I'm unique in the quad world. There are few people that either have the passion for wheeling long distances and stuff, or have the capacity, or energy or whatever". Multiple barriers and facilitators were apparent for PA022, but he believed that his passion for wheeling was the main driving force behind his physical activity participation. PA019 also articulated that participation is dependent on the individual: "Most people that are heavily inclined to exercise will find a way. Someway, somehow… There's all kinds of activities... If you're really inclined, you'll find something... Some people don't mind the work. Some people go to the gym every day... that's just in their DNA. Some people don't have that in their DNA". Lastly, PA20 expressed a similar opinion, as he said: "I think with most people with SCI ... it's either you are lazy and don't want to do anything or you are just the type of person that likes to just go out and do it .... I think it's up to the person really". These participants thus contended that an individual's physical activity levels were largely dependent on their personal characteristics. This was perhaps not surprising given the physical activity level of the participants.

4.4 Discussion

The key barriers in this study fell under the broad themes of access and body, while key facilitators included access and structure. Notably, access was both a barrier and facilitator to physical activity participation, highlighting the importance of access to opportunities for physical activity for individuals with SCI. These factors can be situated within the levels of the social ecological model of physical activity participation, specifically the intrapersonal, interpersonal, institutional, community and policy levels.[71]

Intrapersonal Factors

This study found that injury, soreness and finite energy were bodily barriers to physical activity, which are on the intrapersonal level of influence of the social ecological model. These findings are in agreement with previous work showing that physical health issues,[67] pain,[78,132–134] lack of energy[65] and fatigue[78] are barriers to physical activity participation for individuals with SCI. For example, shoulder soreness was a key issue for one of the participants in this study, which is in line with work showing that pain intensity was inversely related to physical activity participation in individuals with SCI.[133]

In contrast to previous work showing that mental health issues and the loss of an 'able identity' are barriers to physical activity participation, no participants reported psychological factors as barriers in the present study.[66,67] For example, Kinne and colleagues (1999) found that lower motivational barriers were predictive of self reported exercise maintenance in individuals with long term mobility impairments, while external barriers (i.e. factors beyond the intrapersonal level) were not predictive of exercise maintenance.[69] The authors cautioned, however, that the participants were highly educated and a portion of them were recruited from a specialized, supportive exercise class, which may have reduced the impact of motivational barriers on exercise participation. Additionally, the authors explained that the theoretical boundary between intrapersonal and external barriers was hard to maintain in practice, which may have resulted in measurement error.[69] Specifically, one participant may have classified an issue as "being too tired" or "not being interested" while another may have cited a cost issue, realizing that lower cost of a program would require less energy to participate, and would increase the chances of being interested.[69] That psychological barriers were not identified in the present study is likely a reflection of the specific limitations of the sample (i.e., limited sample size and high activity level) and not that these barriers are not important in this population *per se*. Furthermore, psychological barriers may not have been identified due to the broad nature of the questions asked, which may have precluded participants from disclosing psychological factors impacting participation. Additionally, comparisons between studies can be difficult due to the subjective nature in which barriers are categorized. Finally, the cross-sectional design of this study may have limited our ability to study the effect of psychological factors on behaviour.

Finally, although we did not identify psychological barriers to physical activity in individuals with SCI, three participants expressed that physical activity participation is largely dependent on personal character. This observation is noteworthy, as placing the burden on personal character discounts influences beyond the intrapersonal level, and implies that it could be unachievable for sedentary individuals to become highly active despite alleviating external barriers. The participants in the present study were highly active and self-selected to participate in the study, which likely explains the opinion that physical activity participation is dependant almost entirely on individual characteristics. Importantly, such a concept could be damaging if internalized by less active individuals with SCI, who may in fact face greater societal barriers to physical activity participation.

Interpersonal Factors

The second level of the social ecological model includes interpersonal factors.[71] At the interpersonal level, we found that social support as a form of structure, including the support of family and a coach, facilitated physical activity participation. Conversely, lack of social support was a barrier to physical activity in some preferred physical activities for participants in this study. These findings agree with previous work showing that social support is a key strategy to overcome barriers,[135] and an important facilitator to participation.[66,67] Further, negative societal attitudes have also been identified as key barriers to physical activity participation;[66] however, these were not discussed by participants in this study. While we acknowledge that participants may have perceived negative societal attitudes as a barrier in the past closer to their time of injury, the focus of the present study was on the recent physical activity monitoring period for highly active participants. The high activity level of the sample and focus on the recent past could explain why negative societal attitudes were not an issue.

Institutional Factors

Our findings on inaccessible facilities and distance to accessible facilities can be categorized as barriers at the institutional level of the social ecological model.[71] The finding that facility access is a barrier to physical activity is common across multiple studies.[66–68,134] On the other hand, we identified living in an environment with numerous opportunities for physical activity was a key facilitator at the institutional level of influence. Another key factor previously identified as a barrier to physical activity at the institutional level is the lack of easily available information about physical activity participation for individuals with SCI, including limited disability specific knowledge of recreation and health sector staff.[66,70] The lack of information/knowledge was not discussed by participants in this study as a barrier, possibly because they were recruited through

ICORD, where there is a resource centre and an adapted gym with knowledgeable staff. Some of the participants were also previously involved in specialized adapted sports programs, and one was himself a personal trainer specializing in training people with disabilities. Thus, it is unsurprising that lack of knowledge was not identified as a barrier in this group of participants given the specialized nature of the local SCI research institution participants were recruited from.

Community Factors

The community level in the social ecological model includes relationships among organizations and groups.[71] At the community level, the lack of accessible equipment was an important barrier preventing participants from being active. Equipment access was identified in previous work as an important barrier to physical activity for people in Canada, the United States, and Sweden.[66,68,135] In the present study, even a highly active, knowledgeable former athlete was still limited by the lack of adaptable equipment, highlighting the salience of this issue. Due to their unique background, this participant was able to circumvent equipment barriers and maintain a high level of activity. For individuals without such a background, however, difficulties in accessing equipment could potentially inhibit participation entirely. While equipment access acted as a barrier to physical activity, we also equipment to be a facilitator to physical activity participation. For example, one participant owned home exercise equipment, which he described as critical to maintain his physical activity levels. This participant relied on assistance to use the equipment, highlighting how a community factor can interact with an interpersonal factor to impact participation.[68] His proximity and access to equipment emphasize the importance of this barrier. The last community level factor identified in this study was warm weather, which facilitated physical activity participation and served to attenuate the barrier of physical soreness experienced by one person. This further exemplifies how barriers and facilitators of different levels of influence are interwoven by demonstrating the interaction between the community and intrapersonal levels of influence.

Policy Factors

At the policy level, the single barrier identified in the current work was the high cost of physical activity participation. While high cost is to be expected in an expensive urban centre such as Vancouver, this barrier has also been identified in areas that likely have lower cost of living. [65,134] In contrast, we found that low cost acted as a facilitator to physical activity participation, for example, free access to the unique Physical Activity Research Centre at our institution encouraged participation.

Reasons for Doing Physical Activity

Participants' main reasons for doing physical activity were because it felt good physically and psychologically, and in order to maintain function. These findings align with those of Papathomas and colleagues, who identified three key physical activity narrative types utilized by people with SCI to frame their physical activity participation.[136] These three narrative types included "exercise is restitution", "exercise is medicine", and "exercise is progressive redemption." Relevant to the findings of the present study is the "exercise is medicine" narrative, which is a story of improved health through physical activity participation. This narrative could pertain to both physical and psychological benefits of physical activity, both which were discussed as reasons for doing physical activity by participants in the present study. The authors explain that narratives are not merely stories people tell, but they can shape thoughts and actions and motivate change. The highly active participants in the present study ascribed to this narrative, which supports the recommendation of Papathomas and colleagues that physical activity promotion interventions must inspire people with SCI to buy into the "exercise is medicine" narrative in order to be effective.[136]

Impressions of Physical Activity Monitoring Data

There was a range in the perception of individual physical activity monitoring data, demonstrating that participants thought differently about what counts as physical activity, and the intensity of physical activity. Some participants either accepted the monitoring data as accurate, subsequently modifying their perceptions of their activity, while one participant completely rejected the monitoring data as inaccurate. This novel insight into impressions of physical activity monitoring data of individuals with SCI supports the notion that quantitative measures of physical activity should be supplemented with qualitative measures to gain a more complete picture of physical activity participation.

Summary

The identified barriers and facilitators to physical activity participation in this study were situated across all levels of influence of the social ecological model of physical activity, including intrapersonal, interpersonal, institutional, community and policy levels. In addition to demonstrating that multiple levels influence physical activity participation, these findings demonstrate the complex interdependence of the levels of the social ecological model. Our findings support the recent recommendation by Martin Ginis and colleagues (2016), which describes collaborative physical activity promotion intervention with the goal of targeting multiple levels of influence.[70] Specifically, they recommend that health care providers, researchers and recreation sectors should work together to target the community, institutional, interpersonal, and intrapersonal levels.[70] Additionally, they emphasize a need for policies to reduce financial and transportation barriers to physical activity participation for people with

SCI.[70] Put together our results are in line with these goals, as we found barriers on multiple levels even in a group of highly active participants.

4.4.1 Limitations

These results are based on a small, relatively homogenous sample of men with SCI who use manual wheelchairs. These men are highly active, representing a minority of people with SCI. The voices of less active people, power wheelchair users and women with SCI are not included in this study. While we recognize this limitation, the barriers and facilitators identified in the current work are largely in line with previous work that has included a larger proportion of females, power wheelchair users, and a range of injury levels, age, and range self-reported activity levels.[66–69,134,135] However, our work and that of others included primarily Caucasian males.[68,69] As such, more work is needed investigating factors impacting physical activity participation for women with SCI as well as in samples with more ethnic diversity.

Concluding Remarks

In the presented work I evaluated the utility of group based wrist-worn accelerometry cut points to estimate physical activity intensity during a monitoring period in individuals with SCI. Further, I investigated the relationship between cardiac function and physical activity participation during the monitoring period, and further explored the physical activity monitoring data through qualitative interviews discussing the factors impacting physical activity participation.

I found that group-cut points over or under estimated MVPA compared to individual cut points. Individual calibration of wrist-worn accelerometry against energy expenditure should thus be performed to better estimate physical activity participation. Next, I found that total MVPA, wheeled MVPA and nonwheeled MVPA were each associated with global systolic cardiac function independent of injury level, whereby those with the highest MVPA had the best systolic cardiac function. These results suggest that individuals with SCI of all injury levels should participate in MVPA for optimal cardiac function. Lastly, I found several barriers and facilitators to physical activity participation for participants in study 3, both on an individual and societal level, and that meanings of physical activity and impressions of the physical activity monitoring data varied between individuals.

Individually calibrated wrist-worn accelerometry was a useful method to objectively measure physical activity in individuals with SCI, and shows promise as a tool to investigate the relationship between physical activity participation and chronic disease risk in this population. Wrist worn accelerometry could be used to generate population level data on physical activity participation, inform evidence based guidelines for physical activity participation, and ultimately improve health in people with SCI. Our findings on the relationship between cardiac function and MVPA are exciting because this relationship was independent of injury level, suggesting that physical activity is important for heart health in individuals with SCI of all injury levels. These findings also help lay the groundwork for developing evidence based guidelines for physical activity participation for people with SCI. Despite the high activity level of the participants in the qualitative interviews, there were still several barriers to participation, indicating that interventions to improve physical activity participation should target multiple levels of influence, especially broader societal levels to decrease barriers to participation. I suggest that objective measures of physical activity and health should be supplemented with qualitative measures to gain a better understanding of physical activity participation in individuals with SCI, with the ultimate goal of improving overall health and quality of life for this population.

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Appendices

Appendix A Interview Schedule

Interview Schedule: Barriers and Facilitators of Physical Activity Participation during a 7-day Physical Activity Monitoring Period

The following questions represent an overarching agenda for interviews with study participants. The questions will be pursued flexibly and may be altered and added to over time as different themes and patterns emerge in the data.

1. I was wondering if you could start by telling me what the seven-day physical monitoring period was like for you.

   Probes:

   - How physically active were you over the seven days? Please talk me through each day in terms of the physical activities you engaged in.
   - Which days were you more/less physically active and why?
   - How did the monitoring period compare to a typical week for you?
     - If different, how was it different and why?
   - Which physical activities did you enjoy more/less? Why?
   - Who did you do physical activities with and why?
   - How did you get to the location of the physical activities?
   - What financial costs did you incur for the various physical activities you did over the week?
   - What barriers to physical activity did you encounter over the week?
   - What were some of the factors that supported you in being physically active over the week?
   - Were there any physical activities that you wished you could have done or done more of over the week? If yes, what constrained you?

- Were there any physical activities that you did more or less of than usual? Why? What was that like for you?

2. I would like to show you the accelerometer data. (Point out highs and lows in the physical activity data before asking questions listed below)

   Probes:

   - What were you doing at these moments?
   - Who were you with?
   - Where did the physical activities or physical inactivity take place? How did you get there?
   - Why you were more/less active at these particular moments compared to other days/times?
   - How did you feel about those moments where you were more/less physically active? (Ask about enjoyment or lack of enjoyment)

3. Just to conclude, I'm wondering if you have any thoughts about what policy or practical changes are needed to make it possible for more people with SCI to be physically active?