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Exercise guidelines to promote cardiometabolic health in spinal cord injured humans: time to raise the intensity?

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Title: Exercise guidelines to promote cardiometabolic health in spinal cord injured humans: time to raise the intensity?

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influences habitual levels of physical activity and hence cardiometabolic health. Performing regular structured exercise therefore appears extremely important in persons with SCI. However, exercise options are mainly limited to the upper-body, which involves a smaller activated muscle mass compared to the mainly leg-based activities commonly performed by non-disabled individuals. Current exercise guidelines for SCI focus predominantly on relative short durations of moderate-intensity aerobic arm cranking exercise, yet contemporary evidence suggests this is not sufficient to induce meaningful improvements in risk factors for the prevention of cardiometabolic disease in this population. As such, these guidelines and their physiological basis, require reappraisal. In this special communication, we propose that high-intensity interval training (HIIT) may be a viable alternative exercise strategy, to promote vigorous-intensity exercise and prevent cardiometabolic disease in persons with SCI. Supplementing the limited data from SCI cohorts with consistent findings from studies in non-disabled populations, we present strong evidence to suggest that HIIT is superior to moderate-intensity aerobic exercise for improving cardiorespiratory fitness, insulin sensitivity and vascular function. The potential application and safety of HIIT in this population is also discussed. We conclude that increasing exercise intensity could offer a simple, readily available, time-efficient solution to improve cardiometabolic health in persons with SCI. We call for high-quality randomised controlled trials to examine the efficacy and safety of HIIT in this population.

Key words: Spinal cord injury, Cardiometabolic health, High-intensity interval training, Vigorous-intensity exercise, Cardiorespiratory fitness

FMD- flow-mediated dilation,

HbA1c- glycated haemoglobin,

HDL-C- high-density lipoprotein cholesterol

HIIT- high-intensity interval training,

HRmax- maximum heart rate,

LDL-C- low-density lipoprotein cholesterol

MICT- moderate-intensity continuous training,

OGTT- oral glucose tolerance test,

PAG-SCI- physical activity guidelines for people with a spinal cord injury,

RPE- rating of perceived exertion,

SCI- spinal cord injury,

SIT- sprint interval training,

T2DM- type-2 diabetes mellitus,

$\dot{V}O_{2peak}$ - maximal oxygen uptake.

Spinal cord injury (SCI) creates a complex pathophysiology, characterised by paralysis, which has wide-ranging implications for multiple body systems. For persons with SCI, chronic cardiometabolic diseases occur at a heightened frequency and earlier in the lifespan compared to non-disabled individuals [1-3]. Given that more than 2 million people currently live with SCI worldwide and the incidence of SCI is highest among young adults [4], it is clear that there is an increased and prolonged demand on medical and support resources for persons aging with paralysis. Despite the known, undisputed health benefits of physical activity in non-disabled individuals [5-7], research suggests patients with SCI perform little to no physical activity [8-11], and this is likely a key driver of the greater prevalence of cardiometabolic disease in this population [12, 13]. Therefore, it is a priority to develop evidence-based, effective physical activity recommendations for the prevention of chronic disease in persons with SCI.

The recently re-published Physical Activity Guidelines for Spinal Cord Injury (PAG-SCI) recommends at least 20 minutes of moderate to vigorous-intensity aerobic exercise twice a week (40 min/wk) [14], while a recent position statement from Exercise and Sports Science Australia recommends ≥150 min/wk of moderate-intensity or ≥60 min/wk of vigorous-intensity exercise [15]. Both of these guidelines also include strength training ≥2 day/wk [14, 15]. Regardless of the large discrepancy between these guidelines in terms of the recommended volume of moderate-intensity exercise, they remain indifferent from the *minimum* amount of exercise which is promoted by reputable, international health authorities [Centers for Disease Control (CDC) and World Health Organisation (WHO)] in order to reduce the risk of developing cardiometabolic disease in the general cycling), whereas exercise for persons with SCI is primarily restricted to the smaller upper-body skeletal muscles [e.g. arm-crank exercise or wheelchair propulsion]. As a result of the smaller active muscle mass and blunted haemodynamic responses with SCI, the absolute capacity for physical exercise is reduced [16-18]. Therefore, at the same relative intensity, the absolute energy expenditure, cardiovascular strain, and whole-body metabolic demand, will always be lower during moderate-intensity arm-crank exercise or wheelchair propulsion compared with moderate-intensity walking or cycling. The ability for skeletal muscle to adapt to the same stimulus will not be reduced; however, the smaller active muscle mass means that modest training-induced adaptations in the arm are less likely to impact biomarkers of cardiometabolic health. As such, to promote a *lower* volume of exercise in this population would seem physiologically counterintuitive, whilst promoting a *similar* volume of exercise would likely be less effective. In accordance with this, a recent randomised controlled trial demonstrated that performing PAG-SCI for 16 weeks was insufficient to promote clinically meaningful changes in both novel and traditional biomarkers of cardiovascular disease (CVD) [19]. Moreover, a systematic review requested by the Consortium for Spinal Cord Medicine [20] concluded that the current evidence is insufficient to determine whether these volumes of exercise are associated with positive changes in carbohydrate and lipid metabolism (and associated disorders) amongst adults with SCI. Therefore, we contend that these guidelines, and their physiological justification, require reappraisal, and that there is need to develop more effective, alternative approaches.

return in persons with SCI blunts cardiac output , which can lead to an early onset of muscle fatigue [26], thus reducing ones capacity for prolonged exercise. Therefore, promoting a *larger* volume of moderate-intensity exercise might not be feasible in this population. Functional electronic stimulation [27-30] and body weight supported treadmill training [31], have received considerable research attention, but have numerous practical limitations (i.e. significant cost and specialist resources required), and may have limited application outside the laboratory. One potential alternative approach, which has received less attention, would be to recommend high-intensity interval training (HIIT) as a practical means of increasing vigorous-intensity exercise. The benefit of vigorous-intensity physical activity is supported by a number of epidemiological studies, albeit in non-disabled individuals, demonstrating superior reductions in the risk of cardiovascular [32, 33] and all-cause mortality [34-36], in comparison to light-to-moderate intensity physical activity. Moreover, accumulating evidence, from studies applying HIIT in non-disabled populations, demonstrates that HIIT promotes superior peripheral [37] and whole-body adaptations [38-40], compared with moderate-intensity continuous training (MICT). HIIT may therefore offer a simple, more effective alternative to current approaches for improving cardiometabolic health in persons with SCI. In the following sections we put forward the case for recommending HIIT in SCI, and subsequently consider its potential practical application and safety in this population.

HIIT encompasses exercise performed above the intensity which elicits the maximal lactate steady state. Any exercise above this threshold results in the progressive accumulation of intramuscular and systemic metabolites that are implicated in fatigue. As such, exercise intensities above this threshold (~80-85% $\dot{V}O_{2peak}$) cannot be maintained for a prolonged period of time. The exercise must therefore be performed in intervals interspersed with periods of low-intensity or resting recovery. The main justification for HIIT is that it allows a greater volume of vigorous-intensity exercise to be accrued in a single exercise session, and accumulating evidence suggests that this can be of great physiological and clinical benefit [38-40].

A wide range of HIIT protocols have been utilised in the literature but with limited standardisation of the terminology used to classify different protocols. Furthermore, studies have prescribed exercise intensities as a percentage of different maximal physiological responses [e.g. maximum heart rate (HRmax [41]), heart rate reserve [42], age-predicted max heart rate [43] and peak oxygen uptake ($\dot{V}O_{2peak}$ [44])] and, for these reasons, may not be directly comparable, particularly in individuals with low baseline fitness [45]. Nevertheless, for the purposes of this review, we adopt the terminology proposed by Weston *et al*, [38], whereby HIIT describes protocols using intensities between 80-100% of HR_{max}, whereas protocols using 'all-out' efforts, or efforts ≥100% $\dot{V}O_{2peak}$, are referred to as sprint interval training (SIT) (Figure 1). There is good evidence that both HIIT and SIT provide equal or even superior physiological adaptations compared with MICT [46-50]. However, as SIT protocols may be more difficult to adapt in order to protocols tested in both the SCI and non-disabled literature are described in Table 1.

[INSERT FIGURE 1 ABOUT HERE]

[INSERT TABLE 1 ABOUT HERE]

3 Moderate vs Vigorous-intensity Exercise for Cardiometabolic Health

3.1 Cardiorespiratory Fitness and Skeletal Muscle Oxidative Capacity

Poor cardiorespiratory fitness has been widely reported in individuals with SCI [52, 53]. Although just ~90 min/wk [44, 54] of MICT is sufficient to promote modest improvements (~10%) in $\dot{V}O_{2peak}$, a substantially larger volume (180 min/wk) is necessary for greater improvements (~19%) [55]. Vigorous-intensity exercise offers superior benefits and is more time efficient. Of the two studies which have used time-matched training protocols in SCI (Table 2) there are negligible (12% vs. 10%) [42] and considerable (50% vs. 17%) [56] improvements in $\dot{V}O_{2peak}$ with vigorous-intensity compared to moderate-intensity exercise, respectively. The larger improvement in the De Groot *et al*, [56] study could be due to participants having acute (< 225 days) injuries or the greater volume of accumulated vigorous-intensity activity (additional 48 min/wk). More recently, unpublished data from Sæter [57], which adopted a more robust isocaloric study design, demonstrated a superior stimulus for $\dot{V}O_{2peak}$ and PPO with vigorous-intensity exercise

Several studies have directly compared the effects of energy-matched HIIT and MICT on $\dot{V}O_{2peak}$ in deconditioned (non-disabled) individuals with pre-existing cardiometabolic disease and these have clearly demonstrated that HIIT results in superior improvements. These studies were summarised in a recent meta-analysis which, using data from 10 studies and 273 participants, showed that the increase in $\dot{V}O_{2peak}$ following HIIT was approximately twice (~3 ml/kg/min) that observed following MICT [38]. This finding has been reproduced in various non-disabled populations including healthy young and middle-aged sedentary men [59, 60], overweight and obese men and women [61], and in individuals with type-2 diabetes mellitus (T2DM) [62]. A 3 ml/kg/min improvement in cardiorespiratory fitness is associated with a 15% and 19% reduction in all-cause and CVD mortality, respectively, and is on par with a 7 cm reduction in waist circumference, a 5 mmHg reduction in systolic blood pressure, or a 1 mmol/L drop in fasting plasma glucose [63, 64]. Given that cardiorespiratory fitness consistently manifests as the strongest predictor of cardiometabolic disease risk and longevity in epidemiological studies [65-68], these findings are an important point of reference in the argument for applying HIIT, as a model to increase vigorous-intensity physical activity, in individuals with SCI.

Although still a subject of debate [69-71], recent evidence supports, at least partially, the role of peripheral muscle characteristics, in particular absolute mitochondrial capacity (i.e. maximal mitochondrial oxygen utilization), in limiting $\dot{V}O_{2peak}$, and hence underpinning changes in $\dot{V}O_{2peak}$ with exercise training [72, 73]. It is noteworthy then that a

. Arm exercise training may not be sufficient to induce central hemodynamic adaptations [74], but can be expected to induce peripheral mitochondrial adaptations. Thus, if the superior effects observed with HIIT compared with moderate-intensity cycling and walking/running in non-disabled individuals are translatable to arm exercise training in persons with SCI, then HIIT may provide a more effective intervention for improving $\dot{V}O_{2peak}$ in persons with SCI. Moreover, the superior changes in mitochondrial oxidative capacity with HIIT may have implications for other cardiometabolic risk factors such as insulin sensitivity and glycaemic control [75].

[INSERT TABLE 2 ABOUT HERE]

3.2 Insulin Action and Glycaemic Control

Insulin resistance is a pre-requisite to T2DM. It is characterised by the failure of insulin to exert the normal cellular effects on various tissues, leading to the impairment of insulin mediated glucose disposal. Fasting hyperglycaemia can persist due to the insensitivity of the liver to the suppressive effects of insulin on gluconeogenesis and reduced glycogenolysis [76]. Consequently fasting plasma glucose concentrations have been shown to correlate with basal rates of hepatic glucose output [77]. Therefore, as fasting plasma glucose concentrations tend to be only mildly elevated in individuals with SCI [78], it is most likely that peripheral insulin resistance is the major driver behind impaired glycaemic control in this population. The lack of stimulation and disuse because of paralysis can have a profound impact on skeletal muscle below the level of

[INSERT FIGURE 2 ABOUT HERE]

Recent publications have demonstrated that moderate-intensity arm-crank ergometry improves insulin resistance, as determined by HOMA-IR [87, 88]. Although this is promising, HOMA-IR reflects hepatic insulin sensitivity, whereas indices derived during postprandial oral glucose tolerance tests (OGTT), such as the $ISI_{matsuda}$, represent predominantly peripheral insulin sensitivity [89, 90]. Data from the HOMEX-SCI trial, including both fasting and provocative dynamic testing, would suggest arm-crank MICT (60 – 65% $\dot{V}O_{2peak}$, 180 min/wk) in persons with chronic paraplegia improves hepatic but not whole-body insulin sensitivity [55]. Therefore, moderate-intensity arm-crank exercise might not be sufficient to overcome insulin resistance in peripheral tissues. There is a paucity of research comparing both fasting and dynamic glucose and insulin responses to HIIT or MICT in the context of arm-crank exercise in the SCI population. Insulin sensitivity data from De Groot *et al* [56] is counter-intuitive, in that it demonstrates non-significant improvements in the moderate-intensity group and reduced insulin sensitivity in the high-intensity group. This may be explained by a natural regression to the mean effect (i.e. greater proportion of insulin resistant individuals in the low-intensity group at baseline). These results should be viewed with caution due to the, (i) small sample size (n=3 per group) and, (ii) the marked age and sex differences between the two groups, which could impact exercise responses.

studies. Their analyses demonstrated that HIIT was associated with improved insulin sensitivity (estimated via fasting or OGTT-derived indices) and reduced fasting glucose when compared to both baseline and/or changes in a no-exercise control group [40]. The magnitude of change appeared to be greater in populations with insulin resistance (e.g. T2DM or metabolic syndrome) with reductions in glycated haemoglobin (HbA1c) also observed in this group [40]. When compared with MICT there appeared to be greater improvements in markers of insulin sensitivity with HIIT (both fasting and dynamic combined), but no difference in the change in fasting glucose, insulin or HbA1c in isolation [40]. These differences were apparent despite the fact that the methods varied considerably between studies. This included variations in the HIIT protocols utilised (e.g. SIT vs HIIT, cycling vs running), the techniques used to assess insulin sensitivity (e.g. fasting vs OGTT vs clamp) and the duration after the final training session in which the insulin sensitivity data was captured. Moreover, studies had been performed in a wide variety of populations. As such, there is sufficient evidence that in non-disabled populations with insulin resistance HIIT is associated with superior changes in markers of insulin sensitivity compared to MICT [62, 91-95].

It is also important to consider the acute effects of MICT and HIIT on glycaemic control, although this has received less research attention, especially in SCI individuals. Two studies have examined the acute effects if HIIT vs MICT on glycaemic control, using continuous glucose monitors to capture 24-hour glucose profiles, and have shown superior effects with HIIT in both obese men [96] and individuals with T2DM [97]. These effects are underpinned by a plausible mechanism given that high-intensity exercise is exercise . Clearly, the acute effects of exercise, as well as comparisons of HIIT and MICT, on glycaemic control in SCI individuals, is an important area of future research.

3.3 Vascular Function and Blood Pressure

Arterial stiffness [102] and endothelial function [103, 104] are important predictors of future cardiovascular health. Individuals with SCI are characterised by severe deterioration of structure and function of vessels below the level of injury [105], but evidence also suggests increased stiffness and impaired endothelial function within central and regional upper body arteries in SCI relative to non-disabled controls [106]. Recent evidence suggests that achieving the PAG-SCI for 16-weeks is insufficient to improve the health of both lower and upper-limb, as well as central blood vessels [19].

A recent meta-analysis, including 182 participants from 7 studies, demonstrated that HIIT was superior to MICT for improving markers of endothelial function [39]. Within the meta-analysis, studies that had utilised a work-matched HIIT protocol, consisting of 4 x 4 min at 85-90% HR_{max}, appeared to show the most consistent benefit of HIIT over and above improvements observed with MICT [61, 91, 107, 108]. A 1% increase in FMD (flow-mediated dilation) is associated with a 13% reduction in the risk of cardiovascular events [103]. Therefore the 2.6% magnitude of difference in the change in FMD observed between HIIT and MICT in this meta-analysis would be expected to result in clinically meaningful risk reduction [39].

suffer from hypotension . A direct comparison of moderate and high-intensity exercise training on blood pressure is not available in SCI. However, in non-disabled individuals, evidence suggests that several months of HIIT or MICT are able to induce comparable changes in both systolic and diastolic blood pressure in a variety of populations [60, 61, 91, 111].

3.4 Body Composition

Individuals with SCI demonstrate a greater propensity to accumulate excess body fat compared to non-disabled populations [112, 113]. Furthermore, due to the accelerated loss of lean mass, the distribution of adipose tissue in SCI also appears to be altered [114], which would be expected to exert detrimental metabolic effects [115-118]. It is therefore important to consider the role physical activity plays in maintaining body composition and the potential contribution towards a sustained energy deficit to reduce adiposity. Yet, large additions to weekly total energy expenditure (TEE) through structured exercise (i.e. on top of baseline physical activity) are required to induce meaningful reductions in body fat [119]. For example, Donnelly *et al,* [120] suggested that a meaningful body mass reduction requires an exercise energy expenditure in excess of 2000 kcal/wk. If we extrapolate from exercise data for inactive SCI participants in the HOMEX-SCI trial [55], achieving this would require approximately 448 min/wk of moderate-intensity arm-crank exercise. Therefore, it is perhaps not surprising that following PAG-SCI for

There is good evidence from non-disabled studies that HIIT can be an effective intervention for promoting positive changes in body composition, including reductions in total body mass [59, 91, 121-123], total fat percentage [122-125], total abdominal fat mass [91, 122-124] and waist circumference [91, 122, 126]. However, perhaps as expected, studies that have compared energy-matched HIIT and MICT interventions (i.e. both interventions would increase TEE to a similar extent) over several months have demonstrated comparable changes in body composition [61, 91, 121]. Interestingly, it also appears that HIIT protocols requiring lower exercise volumes (e.g. low-volume HIT or SIT) are associated with similar increases in total 24-hour energy expenditure to 30-50 min of MICT [127, 128] and can also induce meaningful reductions in total and abdominal fat [124, 129], which are comparable to 30-45 min of MICT in overweight/obese individuals [123]. Increases in leg lean mass have also been observed with cycling based HIIT [122, 124], and this has the potential to also translate to the upper-body musculature in patients with SCI. While HIIT does not appear to induce a greater reduction in adiposity than MICT, the reviewed evidence would suggest it is equally as effective, but with a reduction in exercise time commitment.

3.5 Fasting and Postprandial Dyslipidaemia

A recent meta-analysis [130] highlighted that persons with SCI have a unique lipid profile, primarily characterised by depressed high-density lipoprotein cholesterol (HDL-C). Hooker & Wells [42] showed a trend for increased (21%) HDL-C and reduced (-15%)

impact of exercise-intensity on lipid profiles. Greater or similar improvements in HDL-C with HIIT compared to MICT have been shown in populations with cardiometabolic disease [38] and obese young men [131], respectively. Currently the non-disabled literature is unclear as to whether HIIT offers superior adaptations than MICT for lipid profiles [39] [132]. However, over 24 weeks O'Donovan *et al*, [133] demonstrated high-intensity exercise was more effective in improving lipid profiles than MICT of equal energy cost. It is possible interventions of longer durations are required to determine the true-impact of exercise intensity on lipid profiles.

The two studies which have used time-matched training protocols in SCI demonstrated a decrease in fasting triglyceride concentrations (-19% [42] and -31% [56]) pre-post with vigorous-intensity exercise, but no change with moderate-intensity exercise training. Elevated fasting triglyceride concentrations have long been associated with CVD [134, 135]. Despite observing unremarkable concentrations of fasting triglycerides, participants with chronic paraplegia have shown exaggerated postprandial lipaemia [136, 137]. This exaggerated postprandial lipaemia is an important stimulus for the development of atherosclerosis [138], and non-fasting triglyceride concentrations has revealed a stronger association with CVD than fasting [139]. As a result of a more sedentary lifestyle, reduced lipoprotein lipase slows postprandial triglyceride extraction from the systemic circulation and the atrophy of leg lean mass limits the ability to metabolise postprandial triglycerides as a fuel source [140]. To our knowledge, no studies have been conducted looking at the impact of upper-body exercise on postprandial lipaemia in persons with SCI. However, several studies have examined the effect of an acute bout of HIIT on the

HIIT is similarly effective to MICT for reducing postprandial lipaemia.

4 Cardiovascular Safety of HIIT

Concerns have been raised over the safety of HIIT in populations at risk of cardiometabolic disease and this should be specifically considered with reference to SCI. Evidence from one recent non-disabled study, which included 5000 patients undergoing supervised cardiovascular rehabilitation over a 7-year period, suggested that the rate of adverse cardiovascular events was low with both HIIT and MICT, although the event rate was higher with HIIT [126]. Specifically, the study reported an adverse cardiovascular event rate of 1 per ~23,000 exercise hours during HIIT (2 non-fatal cardiac arrests) compared with 1 per 129,000 exercise hours during MICT (1 fatal cardiac arrest) [126]. However, various HIIT protocols have been used safely in patients with post infarction heart failure [142, 143], diastolic dysfunction [144], coronary artery disease [145] and atrial fibrillation [146], while also improving clinical symptoms. A systematic review of laboratory/hospital based exercise training studies in persons with SCI found that adverse events were not common and those that occurred were not serious [147]. It should be noted that the individuals in this review and within the studies mentioned above were subject to extensive screening, and the cardiovascular safety of HIIT in this population therefore requires further scientific appraisal. However, when appropriate pre-participation screening is adopted the risks of adverse events are relatively low and as previously suggested are '*likely comparable with the variant risks observed in the general population'* [148]. SCI-specific special considerations for exercise, including the symptoms and management of autonomic dysreflexia and there is no reason to speculate that the occurrence of this will be increased with HIIT. As with any exercise prescription, it would be recommended that individuals consult their clinician prior to engaging in such exercise training programmes.

5 Considerations for the application of HIIT to SCI populations

Individuals with SCI ≥ T6 exhibit a blunted cardiovascular response due to an absence of cardiac sympathetic innervation [150] and a reduced catecholamine response during exercise [151]. As a result of autonomic dysregulation, HR_{peak} can be as low as 120 b/min· Consequently in these individuals it would be difficult to prescribe an appropriate exercise intensity using heart rate data. Evidence suggests that ratings of perceived exertion (RPE) [152] and a talk test [153] can be effectively used to control exercise intensity in persons with paraplegia. Consequently we advise an RPE ≥16 and 'speaking is not comfortable' as appropriate markers of 'vigorous-intensity' when performing upper-body exercise.

The advantage of HIIT is that it enables deconditioned individuals to do a substantial amount of work at a relatively high-intensity by incorporating rest periods, which reduce local muscular fatigue. Fatigue following an acute 20 minute bout of HIIT in patients with chronic fatigue syndrome was not clinically different to moderate-intensity continuous exercise of a comparable workload [154]. Sensory impairment below the level efficient and incorporates rest periods (ideal for performing regular pressure release) this could mitigate this risk and prevent skin breakdown.

Due to a reduced sweating capacity and inability to dilate superficial vasculature [155], persons with higher-level injuries have an impaired heat loss during exercise [156]. While workload is increased with HIIT, possibly resulting in greater heat production, the total exercise time is less than MICT with recovery periods interspersed throughout. Therefore we have no reason to believe that HIIT would impact core body temperature more than MICT. Still precautions should be taken when persons with SCI exercise in hot environments, as they have impaired thermoregulatory function [157]. Furthermore, to overcome blood pooling in lower extremities, associated with impaired venous return, an adequate cool down should be performed to prevent post-exercise hypotension. Shoulder overuse injuries and musculoskeletal pain are also common in persons with SCI [158, 159]. While the higher workloads necessary to achieve vigorous-intensity might further contribute to these conditions, exercise has been proposed as a feasible, conservative, therapeutic treatment for shoulder pain in persons with SCI [160].

Discussions regarding behaviour change and/or maintenance are outside the scope of this review. However, preliminary evidence would suggest that individuals with pre-diabetic conditions can adhere to HIIT over the short-term (4 weeks) and do so at a greater level than MICT [123, 161]. Questions have been raised regarding the adherence to HIIT over the long-term [162, 163] but we encourage researchers and practitioners to develop and evaluate strategies to incorporate HIIT into the everyday lives of persons were MICT . Reassuringly, unpublished data has also demonstrated persons with SCI experienced greater enjoyment with HIIT and SIT protocols compared to MICT [165]. However, medical over protection may limit the prescription of vigorous-intensity exercise rehabilitation in this population. To help overcome this, the safety and efficacy of HIIT, particularly for persons with acute (<1 year) and higher level (≥T6) SCI would need to be demonstrated by well-controlled longitudinal training studies. This is imperative when vigorous-intensity exercise has the potential to offer significantly greater improvements in certain cardiometabolic outcomes than MICT in a population at increased risk of chronic disease.

6 Conclusions

This special communication presents a case for the utility of HIIT as a strategy to promote vigorous-intensity physical activity and reduce cardiometabolic disease in persons with SCI. Data from SCI cohort studies, albeit collected using suboptimal research designs, seem to agree with consistent findings from studies in the general population that vigorous-intensity is superior to moderate-intensity exercise in improving a variety of cardiometabolic health outcomes. Importantly, these findings can be explained and supported by plausible physiological mechanisms. High–intensity virtual reality arm-exercise is already being investigated in persons with SCI [166] and the National Centre on Health, Physical Activity & Disability (NCHPAD) promote a selection of adapted vigorous-intensity exercise options (e.g. wheelchair burpees).

evidence has been collated concerning the safety and efficacy of HIIT in this population this is merely a call to action for researchers in the field and not necessarily an exercise guideline to be prescribed by clinicians.

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Table 2: Description of exercise training studies that have compared the impact of exercise intensity on cardiometabolic health markers in persons with SCI.

Figure 1: Schematic of sprint-interval training (SIT), high-intensity interval training (HIIT) and moderate-intensity continuous training (MICT) protocols (Adapted from Gibala *et al*, [51] with permission).

Figure 2: Whole body Dual-energy X-ray absorptiometry (DEXA) scan of a female with neurological complete T7 injury sustained 6 years previously (a) and non-disabled female for comparative purposes (b). This figure visually highlights the drastic atrophy of lean mass and accumulation of intramuscular fat in the lower extremities of individuals with SCI.

Table 1

Authors	Exercise Intervals			Recovery Intervals		Total S
	Number	Intensity	Duration	Intensity	Duration	
Little *et al,* [167] N-D Harnish *et al,* [58] SCI	10	90-110% Wmax ≥85% HRmax RPE ≥19	1-min	20-25% Wmax	1-2 min	~2
Tjønna *et al,* [91] N-D Sæter [57 †] SCI	4	~85% Wmax 85-95% HRmax RPE ≥17	2.5-4 min	20-25% Wmax	3-5 min	~3
MacInnis *et al,* [37] N-D Harnish *et al,* [58] SCI	3	~70% Wmax 80-85% HRmax RPE ≥ 16	4-5 min	20-25% Wmax	3-5 min	~3

Table 1 Legend: *HRmax* maximum heart rate, *N-D* non-disabled, *RPE* ratings of perceived exertion, *SCI* spinal cord injury, *Wmax peak*
during an incremental test to fatigue

Suggested frequency for training interventions is 3 sessions/week. Low-intensity warm-up and extended cool-down are not included in
into any applied protocol to optimise circulation and prevent post-exercise hypotension (Evans *et al,* [14]). We have suggested appropriat
can be followed in patients with blunted cardiovascular responses to exercise (spinal cord injury lesions ≥T6). There is scope for variat
frequency, intensity and the duration of the high-intensity intervals, as well as the characteristics and duration of the recovery periods,
nature of the exercise stimulus and thus potentially the physiological adaptations associated with training [168, 169]

† Unpublished data

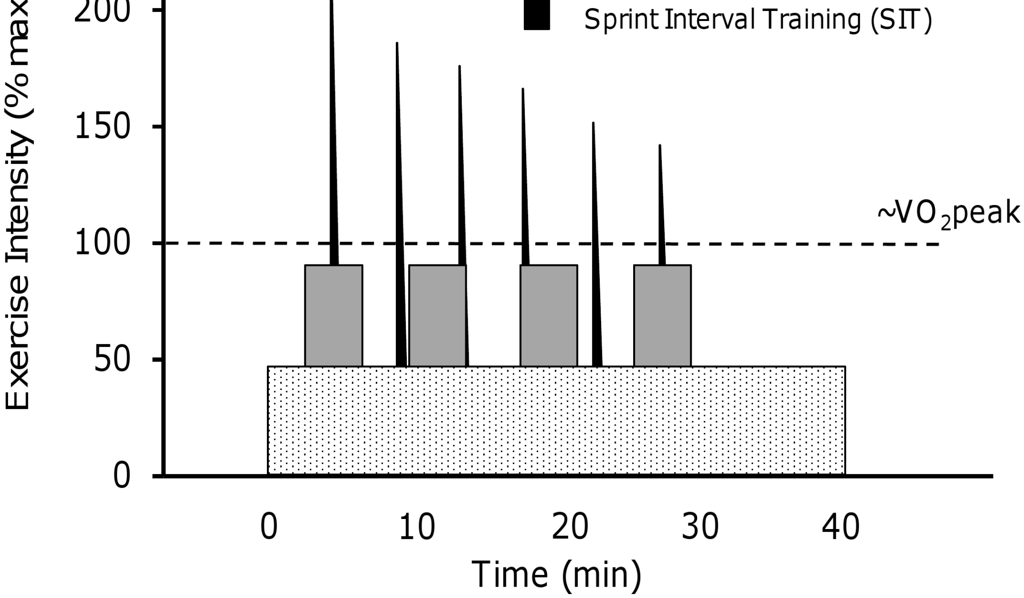
Table 2

Authors	Study Design	Participant Characteristics	Intervention		Outcome Change
Hooker & Wells[42 *]	Pre-post parallel group WERG INT	6 (3F), 5 PARA, 1 TETRA, *TSI;* 4 mo - 19 yr *Age;* 26 - 36 yr	*Frequency*: 3 x wk *Time*: 20 min continuous *Duration*: 8 wks	Moderate-intensity (50 - 60% HRR)	↑ **$\dot{V}O_2$ peak** (10%), ↑ **PPO** (24
		5 (2F), 3 PARA, 2 TETRA, *TSI;* 2 - 19 yr *Age;* 23 – 36 yr		High-intensity (70 - 80% HRR)	↑ **$\dot{V}O_2$ peak** (12%), ↑ **PPO** (13 ↓ **TAG** (96 ± 28 to 78 ± 18 mg/dL; P ↑ **HDL-C** (39 ± 11 to 47 ± 8 mg/dL; P ↓ **LDL-C** (137 ± 26 to 116 ± 5 mg/dL;
De groot *et al,* [56 *]	Pre-post parallel group ACE INT	3 (2F), All PARA *TSI;* 61 - 225 days *Age;* 50 - 54 yr	*Frequency*: 3 x wk, *Time*: 60 min (3 & 2 minute work and rest intervals, respectively. Accumulated activity = 36 minutes) *Duration*: 8 wks	Moderate-intensity (40 - 50% HRR)	↑ **$\dot{V}O_2$ peak** (17%), ↑ **PPO** (24
		3, 2 PARA, 1 TETRA *TSI;* 43 - 175 days *Age;* 20 - 38 yrs		High-intensity (70 - 80 % HRR)	↑ **$\dot{V}O_2$ peak** (50%), ↑ **PPO** (59 ↓**TAG** (-31%), ↓ **IS** (-33%, measured vi CIGMA)
Sæter [57 †]	Pre-post parallel group ACE INT	5, All PARA TSI; 15 ± 11 yrs Age; 43 ± 14 yrs	Frequency: 3 x wk Time: ~ 49 min (373 kcal) Duration: 8 wks Moderate-intensity: 70% peak HR		
		5, All PARA (1F) TSI; 15 ± 14 yrs Age; 46 ± 6 yrs	Frequency: 3 x wk Time: 28 min (including 12 min active recovery) Duration: 8 wks High-intensity: 85 – 95% peak HR (4 x 4 min intervals)		↑ **$\dot{V}O_2$ peak** (9%, trend for an interacti between groups, P = 0.051), ↑ **PPO**

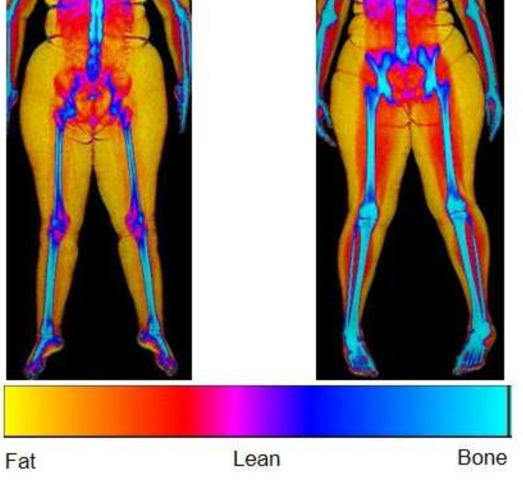
Table 1 Legend: *ACE* arm crank exercise, *HDL-C* high density lipoprotein cholesterol, *HR* heart rate, *HRR* heart rate reserve, *INT* inter
low-density lipoprotein cholesterol, *PARA* paraplegic, *PPO* peak power output, *TAG* triglyceride, *TC* total cholesterol, *TETRA* tetraple
peak oxygen uptake, *WC* waist circumference, *WERG* wheelchair ergometry.

* Note, authors refer to 70-80% HRR between studies as moderate [42] and high-intensity [56], respectively. The terminology to describe e
into moderate (40-60% HRR) and high-intensity (70-80% HRR).

† Unpublished data



Sprint Interval Training (SIT)
~VO2peak
200
150
100
50
0
Exercise Intensity (% max
0
10
20
30
40
Time (min)


Fat
Lean
Bone

- Skipping
- Walking in slow motion (stepping with a one second pause before heel strike)
- Walking with longer strides
- Walking on heels
- Walking on toes

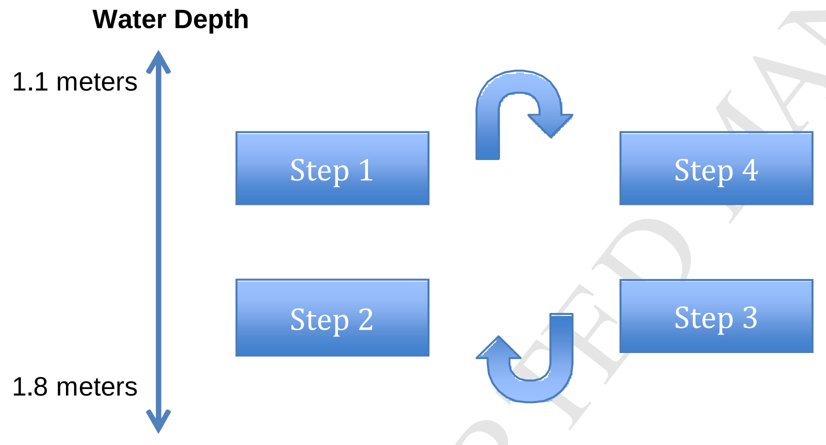
Upper body stretches

- Cervical rotation and side flexion (2 reps x 10 second hold bilaterally)
- Shoulder raises (2 reps x 5 second hold)
- Shoulder rolls (10 reps bilaterally)

Trunk stretches (with aqua noodle)

- Trunk rotation with arms abducted and externally rotated holding the aqua noodle (5 reps bilaterally)
- Arm raises reaching both arms overhead holding the noodle (5 reps bilaterally)
- Side bends pressing the aqua noodle into the water (5 reps x 5 second hold bilaterally)

Gait re-education (20 minutes)



Activity
- Continuous walking
- Stepping up and down off the steps

Progression
- Increase walking speed
- Stepping over steps
- Change of direction (turning)
- Walking with fins (as tolerated)

Strength exercises (10 minutes)

(2 minutes per exercise; 3 exercises selected per class with as many repetitions carried out as possible within the time)

Circuits

- Sit to stand (using pool chair)
- Step ups (progression: raising arms up and down holding the aqua noodle)
- Side step ups
- Trunk rotation (performed standing back to back with a partner, passing ball x 10 reps bilaterally)
- Squats with aqua noodle
- Lunges

Group

- Single leg stand (light finger hold at baseline progressed to 10 seconds with no hand support by session 12)
- Calf raises (10 reps at baseline progressed to 2 sets x 15 reps by session 12)
- Single leg calf raises (5 reps at baseline progressed to 15 reps by session 12)
- Push downs with aqua noodle (15 reps at baseline progressed to 30 reps by session 12)

Cool Down (5 minutes)

(Performed standing by pool wall at water depth level T8 (8^{th} thoracic vertebrae), 30 second hold x 3 reps)

- Quadriceps, hamstring and calf stretches performed using aqua noodle