METABOLIC COST OF UNDERWATER TREADMILL WALKING IN INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

by

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This work is dedicated to my parents and loved ones.

Each of you have always propelled me towards my goals with faithful encouragement.

I am forever grateful for your love and support throughout this long academic career.

I hope I will continue to make you proud.

I love you,

Tyler

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ABSTRACT

Research on the metabolic demand associated with training modalities is needed for those with an incomplete spinal cord injury (iSCI) to improve rehabilitation and exercise prescription approaches. The underwater treadmill (UT) is a method of training and rehabilitation becoming more popular due to the buoyancy related weight reduction and the drag resistance to limb movement. To investigate the metabolic demand of UT exercise, those with and without iSCI (*N* = 8) of similar age were recruited. In the first study, oxygen uptake (VO_2) and heart rate (HR) were measured when exercising at 0.5 and 0.75 mph along with self-selected speeds at ratings of perceived exertion (RPE) of 3, 5, and 7. The self-selected speeds at each respective RPE were also compared. In the second study, cardiorespiratory fitness was assessed using an RPE-regulated graded exercise test in the UT.

There were no significant differences between groups in VO_2 when walking at 0.5 mph, $t(6) = 0.66$, $p = .53$ and 0.75 mph, $t(6) = 0.39$, $p = .71$. The HR was similar between groups when walking at 0.5 mph, $t(6) = 0.93$, $p = .39$ and 0.75 mph, $t(6) = 0.82$, $p = .44$. The VO_2 was significantly different between groups at RPE 7, $t(6) = 2.70$, $p = .04$. The HR between groups was not significantly at RPE 3, 5, or 7 ($p > .05$). For those without iSCI, HR and VO_2 were significantly different between each RPE condition ($p < .05$). Self-selected speeds at each RPE were not significantly different between groups. Self-selected speeds for those without iSCI, were significantly different for each RPE condition. In the second study, mean test duration was similar between groups, $t(6) =$

0.59, $p = .11$. Peak VO_2 was significantly lower for those with iSCI, $t(6) = 3.81$, $p = .03$. Peak HR and RER were similar between those with and without iSCI.

Overall, UT exercise that satisfies the recommendations for aerobic activity level, as prescribed by a 1-10 RPE scale, can be safely performed by those with iSCI. The UT reduces the need for assistive devices such as harnesses, electrodes, and robotics. Further, an RPE-regulated graded exercise test in the UT can safely and effectively be used to test peak cardiorespiratory fitness among those with and without iSCI. Variability does exists between the severity of iSCI and the highest achievable VO_2 during ambulatory exercise, and those with a less severe iSCI may be more suitable for testing maximal VO_2. Further research is needed to develop a protocol to assess maximal VO_2 in the UT, for those with and without iSCI.

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CHAPTER I

DISSERTATION INTRODUCTION

Each year, there are approximately 17,000 new spinal cord injury (SCI) cases in the United States (Jain et al., 2015). White, male adults are the most prevalent population for SCI and injuries commonly involve motor vehicle accidents or falls. Trauma to the spinal cord occurs as contusion, laceration, or dislocation and subsequent threatening inflammatory, apoptotic, and/or ischemic responses (Oyinbo, 2011; Tanhoffer et al., 2007). During the immediate few days after SCI, assessment of functional and neurological classification is necessary to determine the severity of injury (Kirshblum et al., 2011). Evaluation of completeness of injury, motor control preservation, and sensory response is completed using the American Spinal Injury Association's (ASIA) Impairment Scale (AIS; Kirshblum et al., 2011).

After incidence of SCI, individuals are less physically active are more susceptible to musculoskeletal disorders and cardiovascular disease risk factors. Damage to the spinal cord causing denervation can lead to negative muscular structure adaptations and reduced muscle mass, muscular force production and contraction velocity. The occurrence of muscle atrophy as a loss of muscle cross-sectional area is simultaneous with fiber type transformation from slow twitch fibers to the much less fatigue resistant fast twitch fibers (Burnham et al., 1997; Talmadge, Castro, Apple & Dudley, 2002). The progression of adaptations are variable among individuals, but congruently lead to greater muscular fatigue and reduced exercise capacity compared to individuals without SCI (Castro, Apple, Staron, Campos, & Dudley, 1999). Following SCI, the faster onset of fatigue and disuse of skeletal muscle due to graded paralysis increases chances of overuse injuries or discomfort as an individual performs activities of daily living and further impacting quality of life (Giangregorio & McCartney, 2006).

Following SCI, interrupted signaling from higher brain centers has a negative impact on cardiovascular, respiratory, and skeletal responses to exercise. Autonomic nervous system (ANS) dysfunction following SCI negatively affects an individual's capacity for exercise (Jacobs & Nash, 2004). Higher level injuries result in greater consequences as those with an SCI above T5 become primarily dependent upon parasympathetic nervous system withdrawal to the SA node and circulating catecholamines to increase heart rate (HR) during exercise (Claydon, Hol, & Eng, Krassioukov, 2006; Freyschuss & Knutsson, 1969). Injuries with a lesion level below T6, can result in a higher resting HR and exercise HR due to blood pooling in the inactive lower extremities (Paolillo, Paolillo, & Cliquet, 2005). Aerobic exercise capacity (VO_{2Peak}) is commonly reduced among those with a SCI due to the relationship between oxygen uptake (VO_2) and the amount of muscle mass contributing to exercise. Paralysis of the lower extremity reduces the amount of functional musculature and limits the intensity of exercise that can be achieved by an individual (Theisen, 2012). Following a SCI, dysfunctional regulation of blood pressure during exercise, called autonomic dysreflexia, may occur requiring pertinent supervision for observation of signs and symptoms. Typically, individuals with a higher level SCI are at greater risk of experiencing autonomic dysreflexia.

Autonomic nervous system dysfunction following SCI may also impair an individual's thermoregulatory control and subsequently impact the response to exercise.

At rest, individuals with a SCI have subnormal body temperatures due to the loss of hypothalamic feedback limiting cold-sensitive skin receptor responses, such as shivering. Below the level of injury, individuals with a SCI can have a reduced sweating response for a given core temperature compared to those without a SCI (Sawka, Latzka, & Pandolf, 1989). During exercise, individuals with a SCI must maintain thermal equilibrium by relying more on dry heat exchange versus evaporative cooling (Hopman, Oeseburg, & Binkhorst, 1993; Sawka et al. 1989). Reliance upon dry heat exchange will require a greater shift in blood volume to the periphery (i.e. skin), which when coupled with a reduced skeletal muscle pump decreases venous return and leads to a consequent elevation in HR at rest or during exercise (Hopman et al., 1993).

For these reasons, there is a heightened need for those with a SCI to participate in the appropriate modes and intensities of aerobic exercise producing the best possible outcomes. Special considerations exist for those with a SCI participating in aerobic exercise, although more research of the metabolic demand associated with available training modalities is needed to improve rehabilitation and exercise prescription approaches for those with SCI (Riebe, Ehrman, Liguori, & Magal, 2016). Current guidelines suggest selecting modes of aerobic exercise that require the engagement of the greatest amount of muscle mass possible, which would involve both the upper and lower extremities Riebe et al., 2016). Researched methods of improving physical function and cardiorespiratory fitness in those with a SCI include functional electrical stimulation – augmented training, robotic gait training, and underwater treadmill training (Sisto & Evans, 2014).

Underwater treadmill exercise (UT) can allow enough body weight support so that ambulation for individuals with a SCI is more feasible than when using an on land treadmill. For those with a SCI, other aerobic exercise modes that include lower extremity use either require heavy reliance upon physiotherapist help or potentially uncomfortable equipment for mobilizing the lower extremity to achieve appropriate exercise intensities. During UT exercise, the physiological responses to exercise intensifies as the water level decreases due to the change in the amount of the support provided to the body. When the water level is up to the xiphoid process, VO_2 and HR responses have been shown to be either similar or greater for able-bodied individuals participating in UT exercise compared to on land treadmill exercise (Alkurdi, Paul, Sadowski, Dohlny, 2010; Gleim & Nicholas, 1989; Pohl & McNaughton, 2003). Underwater treadmill exercise is safe among those without a SCI, but it is also practical and provides and an ideal environment for those with neurological deficiencies and muscle weakness, such as incomplete SCI (Stevens & Morgan, 2015).

Overall Purpose

There are two studies within this dissertation that examine the responses of individuals with a SCI to exercise on an underwater treadmill. First, a study was designed to measure and quantify the metabolic and cardiovascular responses to a single bout of exercise on an underwater treadmill. In comparison to their age- and sex-matched controls, we hypothesized that those with SCI would produce lower HR and VO_2 values. The second study was designed to elicit maximal cardiovascular and metabolic responses using an original maximal exertion protocol among those with and without SCI exercising in an underwater treadmill. It was hypothesized that although those with SCI would produce lower HR and VO_2 values, both would produce reliable results between two trials of the same protocol.

CHAPTER II

REVIEW OF THE LITERATURE

The beginning of the literature review consists of the etiology, pathophysiology, and epidemiology of SCI along with the evaluation of the injury needed to determine motor and sensory function of an individual. Following, are discussions of the physiological and functional complications involving the cardiorespiratory and muscular systems that arise after the incidence of SCI. The next section includes how thermoregulatory responses are impacted by SCI. The special considerations to cardiorespiratory exercise are discussed, followed by a section on cardiorespiratory training including exercise with functional-electrical stimulation, robotic-assistance, aquatic environments, and more specifically the underwater treadmill. The final section includes a review of cardiorespiratory fitness testing and the effects of different modalities and protocols. The end of this section presents that there have yet to be studies investigating the metabolic demand of underwater treadmill exercise among those with a SCI. It also discusses the lack of investigation of and development of a protocol for testing the maximal aerobic capacity of those with a SCI.

Etiology and Pathophysiology of Spinal Cord Injury

There are an estimated 17,000 new spinal cord injury (SCI) cases each year in the United States (Jain et al., 2015). Most cases involve adult males, with the leading cause of traumatic injury being vehicle crashes followed by accidental falls, and acts of violence such as gunshot wounds (Klebine, 2015). The primary mechanisms of injury to the spine include compression, contusion, and/or laceration, all causing hemorrhage and rapid cell death at the impact site and ultimately leading to subsequent tissue loss (Oyinbo, 2011; Sekhon & Fehlings, 2001). These subsequent responses or secondary mechanisms of injury occur within minutes of injury and may last for weeks (Tanhoffer et al., 2007). Secondary mechanisms of injury are interconnected and may be evident as apoptotic cell death, edema, electrolyte shifts, inflammation, ischemia, neurogenic shock, and/or vascular alteration (Oyinbo, 2011; Sekhon & Fehlings, 2001; Tator & Fehlings, 1991). Hemorrhages and edema may influence ischemia, which has a direct relationship with the severity of the injury developing during hours after SCI (Oyinbo, 2011; Tator & Fehlings, 1991).

Classification and Evaluation of SCI

Following a SCI injury, medical professionals determine the neurological level of injury and the classification of severity (i.e. completeness). The American Spinal Injury Association developed the International Standards for Neurological Classification of SCI to be used as a universal classification tool to objectively classify the level of a SCI (Kirshblum et al., 2011). Systematic examination of dermatomes and myotomes can determine the cord segments affected by the SCI and clarify the extent to which sensory and motor neuron activity remain (Kirshblum et al., 2011). Sensory examination requires bilateral testing of 28 dermatomes (from C2 to S4-5). A 3-point scale is used for assessment of light touch and pin prick sensation via a tapered wisp of cotton and a safety pin, respectively. Using this method, the medical professional can score each dermatome as absent (0), altered (1), normal (2), or not testable (NT). The bilateral pin prick and light touch scores are summed to determine an overall sensory score. The specific level of residual sensory is interpreted as the most caudal, intact dermatome for both pin prick and light touch sensations, determined by the lowest dermatome with a score of 2 (normal).

During examination of motor function, key muscle functions are tested that correspond to 10 paired myotomes (C5-T1 and L2-S1) on the left and right sides of the body. A 6-point scale is used to grade strength. Each myotome can be scored as total paralysis (0), palpable or visible contraction (1), active movement without gravity (2) or with gravity (3), active movement against resistance (4), or normal (5). A summative score is calculated for each upper and lower extremity to provide an overall score for the upper and lower limbs, respectively. The specific level of residual motor function for each side of the body is interpreted as the lowest key muscle function with a score of at least 3, given the preceding muscle function scored a 5.

Following assessment of residual sensory and motor neuron activity, the injury is classified as either tetraplegic (cervical injury) or paraplegic (thoracic or lumbosacral injury). Further, the neurologic severity (completeness) of SCI based upon the objective scoring of sensory and motor functions, as well as sacral sparing (i.e. sensory and motor preservation at S4-5) is determined by the ASIA Impairment Scale (AIS; Kirshblum et al., 2011). The AIS scale ranges from A (complete) to E (normal; Kirshblum et al., 2011). Complete injuries are interpreted as a lack of sensory or motor function at the sacral segments, while an incomplete SCI grade of B refers to only sensory preservation below the neurological level including S4-5. Incomplete grade C is interpreted as motor function preservation below the lesion with over half of the tested muscle functions scoring less than 3 during the motor examination. Incomplete grade D is interpreted as preservation of motor function below the lesion level with at least half of the key muscle functions below scoring at least 3 during the motor examination. A grade of E is assigned when sensation and motor function are graded as normal in all segments during sensory and motor examinations.

Initial damage to the spinal cord results in subsequent harmful responses or mechanisms of further injury such as apoptotic cell death, inflammation, ischemia, or vascular alterations. The cascading impact of SCI warrants post-injury examination that will determine individual degree of functioning as identified by specific classification. This classification assists in determining rehabilitation methods, progression, and anticipated function. As compensatory strategies are implemented, individuals are susceptible to negative muscular adaptations such as atrophy.

Physiological Impact on the Muscular System

Following SCI, the morphological and structural adaptations of the muscular system are similar to those observed following bed rest, weightlessness, and aging (Giangregorio & Blimkie, 2002; Stein & Wade, 2005; Vandenborne et al., 1998). Following bed rest or weightlessness, unloaded skeletal muscle atrophies (i.e. reduction in size and/or number of muscle fibers). In regards to SCI, disuse atrophy is due to the loss of muscle activation following interrupted neural communication from the brain to motor neurons (Gordon & Mao, 1994). In addition to disuse atrophy, individuals post SCI are also susceptible to denervation atrophy caused by damage to spinal motor neurons (Gordon & Mao, 1994). Denervation can alter morphological and physiological muscle characteristics as well as metabolic function of the affected musculature (Boncompagni, 2012; Burnham et al., 1997; Giangregorio & McCartney, 2006; Monroe et al., 1998). In the segments damaged by the SCI, these alterations include reduction of muscle cross-sectional area (CSA), fiber type transformation, preferential fiber type atrophy, contractile and metabolic changes in muscles and, ultimately, increased fatigue.

Muscular adaptations begin rapidly following SCI. Animals observed following surgical transection of the spinal cord, demonstrate hind-limb muscle atrophy approximately 5 days post procedure (Dupont-Versteegden, Houle, Gurley, Peterson, 1998). Human studies of incomplete SCI using muscle biopsies have reported muscle fiber atrophy within 6 weeks of injury (Gorgey & Dudley, 2007). Compared to a control group, thigh CSA of individuals with incomplete SCI was reported 33% smaller (Gorgey & Dudley, 2007). These results are similar to those reported in other studies reporting average muscle CSA 24% to 31% smaller than age- and weight-matched able-bodied controls (Castro et al., 1999; Shah, et al., 2006).

Atrophy of muscle mass and a conversion of muscle composition towards type II fibers results in a loss of force production and oxidative capacity. Within the first few months of paraplegia, affected musculature favors atrophy of type IIa fibers (Biering-Sorensen, Kristensen, Kjaer & Biering-Sorensen, 2009; Castro et al., 1999; Lotta et al., 1991). Later stages of paraplegia (8 to 10 months) result in a more marked atrophy and reduction of type I, slow oxidative muscle fibers, while showing a higher percentage of type IIb fast glycolytic muscle fibers (Burnham et al., 1997; Lotta et al., 1991; Qin, Bauman, & Cardozo, 2010; Scelsi & Lotta, 1991). These changes occur in progressive stages during which type I fibers exhibit a transitional phase of co-expression of slow and fast myosin heavy chain (MHC) isoforms as they transform to type II fibers (Castro et al., 1999; Scelsi, Marchetti, Poggi, Lotta, & Lommi, 1982). The timeline for this transitional period has yet to be specified, but the expression of these hybrid transitional fibers of type IIa and IIx phenotypes may occur as early as 6 weeks and evolve over several years (Burnham et al., 1997; Dudley-Javoroski & Shields, 2008; Lotta et al., 1991; Qin et al., 2010). A timeline of 4 to 7 months post-injury has been suggested for the onset of fiber type transformation. During this transition, there is a down regulation of type I fibers and an up regulation of type IIa and type IIx fibers (Biering-Sorensen et al., 2009; Talmadge et al., 2002). However, histochemical analyses of biopsies from humans, 2 to 11 years post-injury, indicated a complete absence of type I fibers in tested muscles (Andersen, Mohr, Biering-Sørensen, Galbo, & Kjaer, 1996; Castro et al., 1999; Round, Barr, Moffat, & Jones, 1993), suggesting fiber type transformation may continue until a steady state characterized by the predominance of only the fast MHC isoform is reached (Burnham et al., 1997). This transformation in the affected muscles favors faster contractile speeds and a faster rate of fatigue (Castro et al., 1999; Gerrits et al., 1999; Shields, 2002).

A notable increase in muscle fatigue has been reported in animal and human studies from the loss of available muscle mass and progressive transformation of muscle fibers towards type II fibers (Castro et al., 1999; Davey, Dunlop, Hoh, & Wong, 1981; Shields, 2002; Stein et al., 1992). Type II (e.g. fast twitch) fibers have a high glycolytic and a low oxidative capacity and lower endurance than type I (e.g. slow twitch) fibers. The higher proportion of fast twitch fibers results in greater accumulation of metabolic by-products, thus, hindering exercise endurance (Tesch, Sharp, & Daniels, 1981). A loss of muscle capillarization and vascular reactivity following SCI may be additional reasons for heightened muscular fatigue among those with SCI (Chilibeck et al., 1999). The impaired muscle blood flow can result in limited oxygen and energy supply to active muscle as well as attenuate metabolic by-product removal.

In summary, SCI results in interrupted neural communication between the brain and motor neurons and damage to spinal motor neurons. As a result, a reduction in muscle mass and function can lead to reduced muscular force production and contraction velocity. These progressive adaptations vary among individuals, but ultimately result in a state of greater muscular fatigue and a reduced capacity for exercise compared to individuals without SCI. Individuals who have sustained a SCI are also subject to negative consequences relative to the cardiorespiratory system function.

Physiological Impact on the Cardiorespiratory System

Fine control of cardiorespiratory responses stem from the medulla and hypothalamus and are regulated through neurons located in the brain, brain stem, and spinal cord. The hypothalamus coordinates the autonomic nervous system (ANS), which effects blood pressure (BP), heart rate (HR), and respiration. The ANS stimulates and/or inhibits physiological responses via the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS). Modulation of SNS and PNS input occurs via a complex system of feedback loops involving sympathetic afferents that provide excitatory input and parasympathetic afferents that provide inhibitory input to the nucleus tractus solitarius in the medulla oblongata (Garstang & Miller-Smith, 2007; Partida, Mironets, Hou, & Tom, 2016). Activation of sympathetic β_1 adrenergic receptors results in a positive chronotropic effect (increased HR) via more rapid depolarization of the sinoatrial (SA) "pacemaker" node, a positive inotropic effect (increased myocardial contractility), and a positive dromotropic effect (enhanced atrioventricular node conduction velocity; Gordon, Gwathmey, & Xie, 2015). Activation of parasympathetic M_2 receptors results in a negative chronotropic effect (decreased HR) via the Vagus nerve (Gordan et al., 2015). Lastly, activation of β_1 receptors is associated with maintenance of BP and blood volume via hormones released from the kidneys and posterior pituitary gland (Gordan et al., 2015).

It is important to note that SNS nerves (thoracolumbar division) originate from the spinal cord (T1-L2) and radiate outwards to target organs, unlike nerves of the PNS that originate within the brainstem and sacral division of the spinal cord (Gordan et al., 2015). Thus, it is more likely that a SCI will negatively impact SNS regulation of cardiac activity than PNS regulation. Responses to exercise are variable in individuals with SCI depending on level and severity of injury. Dysfunction of the ANS due to spinal cord damage can result in a lower resting HR and oxygen consumption (VO_2), as well as decreased cardiac acceleration and ventilatory and vascular responses during exercise compared to able-bodied individuals (Hopman, Verheijen, & Binkhorst, 1993; Jacobs & Nash, 2004; Silfhout et al., 2016; West, Mills, & Krassioukov, 2012; Zimmer, Nantwi, & Goshgarian, 2007).

At the onset of exercise, linear increases in HR and VO_2 are contingent upon withdrawal of vagal tone and increased SNS input (Astrand, Rodahl, Dahl, & Stromme, 2003; Freema, Dewey, Hadley, Myers, & Froelicher 2006; Freyschuss & Knutsson, 1969). A SCI at or above T5 can limit an individual's exercise capacity due to the loss or impairment of sympathetic outflow from the medullary vasomotor center to the heart. At this level of injury, exercise related increases in HR become primarily dependent upon PNS withdrawal to the SA node and circulating catecholamines (i.e. epinephrine and norepinephrine; Claydonet al., 2006; Freyschuss & Knutsson, 1969; Glaser, Janssen, Suryaprasad, Gupta, & Mathews 1996; Rogers, 1996).

If the lesion level is at or below T6 (i.e. below level of sympathetic outflow), a normal HR response to physical activity is possible, but individuals may exhibit a markedly lower stroke volume (SV; Van Loan, McCluer, Loftin, & Boileau, 1987) and a higher resting HR compared to able-bodied individuals (Jacobs & Nash, 2004; Schmid et al., 1998). This elevated chronotropic activity may be a compensatory mechanism for diminished venous return, blood pooling in the lower extremity (LE), and reduced cardiac preload (Phillips et al., 1998). The impaired or absent vasoresponses in the LE are evident during upper extremity (UE) exercise with a lack of concurrent vasoconstriction within the inactive LE muscles, ultimately leading to venous pooling within the LE (Hopman et al., 1993; Paolillo et al., 2005). The venous pooling results in inadequate circulation of blood back to the heart, thus reducing cardiac preload along with SV as indicated by the Frank-Starling mechanism (Dela et al., 2003; Truijen, Bundgaard-Nielsen, & Van Lieshout, 2010). As a compensatory mechanism, HR increases to maintain cardiac output (Q) and adequate perfusion of blood through the UE (Dela et al., 2003). The amount of blood pooling in the LE depends on the amount of active muscle available to redistribute blood (Hopman et al., 1993). Further, individuals with a SCI above T6 typically achieve higher VO_2 measurements at similar workloads compared to individuals with a SCI below T6 and those without a SCI. In contrast, individuals with a SCI below T6 are capable of achieving similar VO_2 measurements as individuals without a SCI, but may experience exaggerated adrenergic and cardiac responses as compensatory mechanisms to the LE venous pooling if sympathetic outflow is affected.

In those with a SCI, exercise capacity is inversely related to spinal lesion level (Theisen, 2012). In general, those with tetraplegia have a lower peak oxygen uptake (VO_{2peak}) than those with paraplegia (Dela et al., 2003; Hopman et al., 1998; Paolillo et al., 2005; Rogers, 1996). Peak oxygen uptake and lesion level are inversely related due to the amount of functional muscle mass that can be recruited (Coutts, Rhodes, & McKenzie, 1983; Gass & Camp, 1979; Van Loan et al., 1987). Additionally, depending on the level of the SCI, motor innervation can be disrupted to the diaphragm muscle (C3-C5), abdominal muscles (T7-T12), and the intercostal muscles (T8-T12; Paolillo et al., 2005). The ventilator muscles may be less active due to paralysis with a higher level SCI and may lead to decreased inspiration (Silfhout et al., 2016; Winslow & Rozovksy, 2003; Zimmer et al., 2007). Paralysis of abdominal musculature due to lower thoracic lesions may also result in decreased forced expiration compared to able bodied individuals (Crane et al., 1994; Zimmer et al., 2007). Tidal volume during exercise can also be decreased due to poor posture.

Therefore, the level of the SCI impacts SNS input to skeletal muscles, respiratory function, and cardiovascular function leading to changes that can negatively impact aerobic exercise capacity. A higher level SCI (above T6) has a greater impact on cardiac and ventilatory sympathetic innervation compared to a SCI below T6. Individuals with a higher level SCI can experience reduced exercise capacity due to diminished Q, resultant from a lower SV (decreased venous return) and HR (loss of SNS input). A higher level SCI can also limit exercise performance due to a loss of ventilatory muscle activation. Autonomic nervous system dysfunction can also be evident as reflex bradycardia, low resting BP, orthostatic hypotension, exertional hypotension, and autonomic dysreflexia (Bravo et al., 2004; Schmid et al., 1998; Teasel, Krassioukov, & Delaney 2000).

Individuals with SCI may have complications regulating BP. A concerning vascular response during exercise is known as autonomic dysreflexia (AD). Autonomic dysreflexia is characterized by sympathetic reflexive vasoconstriction of the periphery below the level of the lesion (Rogers, 1996). Autonomic dysreflexia can occur in all individuals with a SCI, but those with lesions above T6 (i.e. level of sympathetic outflow) are at highest risk (Krum, Louis, Brown, & Howes 1992). This response is triggered by a nociceptive stimulus (bladder distension) below the lesion level. The sudden BP increase is accompanied by a reflex bradycardia and vasodilation in innervated body parts, but the subsequent dilation of blood vessels is insufficient to counterbalance the rise in BP to dangerously high levels (Karlsson, 1999). Individuals may experience excessive sweating, vasodilation, increased cutaneous temperature, headache, and dizziness. Appropriate measures should be taken to reduce BP such as placing the individual in an upright, sitting position and removal of the triggering factors such as an obstruction of the urinary outlet (Karlsson, 1999). Another complication related to BP regulation is orthostatic hypotension which involves a sudden drop in BP when moving to an upright position. This is caused by the lack of a muscular pump leading to impaired venous return, LE blood pooling, and diminished Q (Jacobs & Nash, 2004).

A SCI above T6 results in interruption of the medullary vasomotor center efferent pathways to spinal sympathetic neurons involved in vasoconstriction, which originate in the T1-L2 spinal segments (Popa et al., 2010). Disruption of supraspinal control and sympathetic tone interrupts normal reflex control of blood vessels below the injury level (Phillips et al., 2012; Popa et al., 2010). A drop in BP characterizing orthostatic hypotension can occur as a result of decreased vascular constriction and a subsequent reduction in venous return (Popa et al., 2010). Similar to orthostatic hypotension, exertional hypotension may occur as a direct result of muscle paralysis and absent vasoconstriction responses in the LE (West et al., 2012). Thus, prevention of normal redistribution of blood flow and maintenance of BP occurs due to interruption in neural control of arterial smooth muscle in non-exercising muscles and the splanchnic bed. Vasodilation occurs in the UE, but may not be compensated by vasoconstriction in LE to support the necessary increase in BP with increasing exercise workloads (West et al., 2012). Coupled with a decrease in SV from inadequate venous return and vasodilation in the exercising muscle, these mechanisms may cause BP to decrease during exercise.

In summary, dependent upon the level of the SCI, aerobic exercise capacity can be negatively impacted. A higher level SCI (T6 and above) will have a greater impact on cardiac and vascular regulation during exercise that results in higher VO_2 consumption at similar workloads compared to lower level SCIs and no SCI. Although individuals with a lower level SCI may achieve similar VO_2 measurements at similar exercise workloads compared to able-bodied individuals, they may experience an exaggeration of adrenergic and cardiac responses to compensate for venous pooling below the level of injury. Individuals with a SCI may also experience complications with BP regulation during exercise such as AD and orthostatic hypotension. Individuals with a higher level SCI are typically at greater risk of experiencing AD. Thus, the effect of SCI on ANS regulation can have implications for CV responses to exercise, but also result in aberrations for thermoregulation during exercise.

Physiological Impact on Thermoregulation

Autonomic nervous system dysfunction following SCI also affects thermoregulation. The impaired thermoregulatory responses to ambient temperatures is termed “partial poikilotherms” (Attia & Engel, 1983). There is reduced afferent input to the hypothalamic thermoregulatory center leading to impaired sweating capacity and shivering response, and disruption of vasomotor control below the level of the lesion (Khan, Plummer, Martinez-Arizala, & Banovac, 2007; Price, 2006). As such, physiological responses to changing environmental temperatures, whether increasing or decreasing, are altered. At rest, individuals with a SCI have subnormal body temperatures of < 97.7°F in environmental temperatures of 72°F-74°F (Khan et al., 2007). Due to the loss of hypothalamic feedback, the response of the cold-sensitive skin receptors to elicit cutaneous vasoconstriction and shivering to preserve heat and increase heat production, respectively, are altered (Khan et al., 2007). During passive heat exposure, individuals with a SCI will have a reduced sweating response (sudomotor) and cutaneous vasodilation (vasomotor) below the level of injury for a given core temperature as compared to those without a SCI (Sawka, Latzka, & Pandolf, 1989). Thus, SCI results in higher core temperatures in hotter environments and lower core temperatures in colder environments (Sawka et al., 1989).

As with other regulatory systems in the body, the magnitude of thermoregulatory impairment is associated with the level and completeness of the SCI (Khan et al., 2007). Thus, a SCI above T6 results in greater thermoregulation impairment (i.e. reduced effector responses) due to a greater loss of sensate skin which limits afferent input into the hypothalamic thermoregulatory centers (Pan, S. L., Wang, Y. H., Hou, W. H., Wang, C. M., & Huang, 2006; Sawka et al., 1989). This is evident as a loss of responsive shivering, sweating, and peripheral blood flow adjustment below the level of the lesion (Garstang & Miller-Smith, 2007). As the level of injury descends, the amount of sensate skin increases, improving thermoregulatory responses (i.e. shivering, vasomotor and sudomotor responses).

In able-bodied individuals, exercise related increases in core temperature have been suggested to be proportional to the increase in metabolic rate, yet independent of environmental temperature (Sawka et al., 1989). Due to ANS impairment below the level of injury, individuals with a SCI must rely more on dry heat exchange rather than evaporative cooling to maintain thermal equilibrium during exercise (Hopman et al., 1993; Sawka et al. 1989; Theisen, Vanlandewijk, Sturbois, & Francaux, 2000). This means that more blood will be shunted to the skin to achieve a greater temperature gradient. The shift of blood volume to the periphery (i.e. skin) accompanied by a reduced skeletal muscle pump decreases venous return and leads to a consequent increase in HR (Hopman et al., 1993). However, fitness level and level of injury may affect the extent of the thermoregulatory alterations (Dawson, Bridle, & Lockwood, 1994; Fitzgerald, Sedlock, & Knowlton, 1990; Price, 2006).

Individuals with a high thoracic injury are susceptible to a greater core temperature and skin temperature in comparison to those with lower level injuries during incremental exercise (Price & Campbell, 2003; Theisen et al., 2003). This is likely due to less available evaporative cooling as sudomotor and vasomotor responses decrease with the elevation of injury. Price and Campbell (2003) showed that high paraplegic and low paraplegic athletes exhibited lower levels of thermal strain during prolonged wheelchair exercise at 60% $VO_{2\ Peak}$ in a warm environment (32°, 55% relative humidity) compared to tetraplegic athletes. It was suggested that this was due to a greater proportion of surface area of skin for evaporative cooling (Price & Campbell, 2003).

In summary, SCI results in impaired vasomotor and sudomotor responses which affect an individual's ability to effectively thermoregulate. Reduced hypothalamic afferent input can result in impaired sweating capacity, shivering response, and vasomotor control below the level of the lesion. Compared to the able-bodied population, individuals with SCI may experience higher core temperatures in hotter environments and lower core temperatures in colder environments. Those with a SCI are also susceptible to increased heat storage during exercise compared to able-bodied individuals. The extent of the impairment is dependent upon the level of injury as available surface area for sweating decreases as the level of injury increases. Depending on the level of injury, ANS dysfunction after SCI can negatively affect aerobic exercise capacity.

Special Considerations for Aerobic Exercise

The lack of published recommendations for designing an exercise prescription program for the SCI population warrants research of training programs and modality options (Riebe et al., 2016). Current aerobic training guidelines for untrained individuals with SCI are 2-3 days each week at a moderate intensity of 40%-59% HR reserve (Riebe et al., 2016). However, muscular fatigue in novice or unfit individuals with SCI may occur before reaching adequate central cardiorespiratory stimulus (Riebe et al., 2016).

More research of the metabolic demand of available training modalities is needed to improve rehabilitation and exercise prescription approaches for those SCI.

Training guidelines suggest selecting modes of aerobic exercise that require the engagement of the largest possible muscle mass (Riebe et al., 2016). However, cycling, utilizing either the UE or LE is a common modality of volitional aerobic exercise for those with a SCI. Although a suitable modality of aerobic exercise for those with little or no LE function, arm cycling recruits smaller musculature, limiting maximal power output and peak VO_2 compared to leg cycling (Astrand & Saltin, 1961). During arm cycling, individuals with a SCI are also more susceptible to diminished venous return as the paralyzed legs reduce the activity of the skeletal muscle pump compared to able-bodied individuals (Hopman et al., 1993). As such, other modalities may provide benefits for cardiorespiratory fitness and functional independence. Training methods such as locomotor training and use of an underwater treadmill (UT) allow use of the large, LE musculature and simultaneously provide step training. However, limited research exists on the effectiveness of these interventions on cardiorespiratory fitness in those with a SI. Further, there is a lack of comparison studies and consistency among existing data, making it difficult to determine best practices.

Cardiorespiratory Training for Individuals with SCI

Following injury, individuals with SCI are susceptible to deconditioning and a reduced functional capacity. Further, individuals with mobility impairments and poor cardiorespiratory fitness are more susceptible to cardiovascular disease risk factors due to a tendency to be more sedentary and participate less in exercise (Cowan & Nash, 2010; Rimmer, Riley, Wang, Rauworth, & Jurkowski, 2004; Sisto & Evans, 2014). Autonomic nervous system dysfunction and diminished control of large musculature associated with SCI can make it difficult for individuals to achieve sufficient cardiovascular exercise intensities for achieving health and fitness benefits (Sisto & Evans, 2014). Thus, appropriate exercise intervention strategies and guidelines are necessary for individuals with SCI. Researched methods of improving physical function and cardiorespiratory fitness in those with a SCI include functional electrical stimulation (FES) –augmented training, robotic gait training, and UT training (Sisto & Evans, 2014).

Functional Electrical Stimulation

Functional electrical stimulation is a technique that requires the application of intermittent electrical current to excitable, paralyzed nerve tissue as a means of eliciting muscular contraction and functionally useful movement (Peckham & Knutson, 2005). It is common for the gluteus maximus, quadriceps, hamstrings, and tibialis muscles to be stimulated during FES exercise (Deley, Denuziller, & Babault, 2015). Functional electrical stimulation can be applied during various forms of exercise such as cycling, rowing, and treadmill walking (Deley et al., 2015; Lindquist et al., 2007). Following FES training, several beneficial physiological adaptations have been reported for those with a chronic SCI. Long-term effects of FES exercise include preventing muscle atrophy (Baldi, Jackson, Moraille, & Mysiw, 1998), eliciting muscle hypertrophy (Crameri, Weston, Climstein, Davis, & Sutton, 2002), improving VO_{2Peak} (Wheeler et al., 2002), and increasing walking speed (Field-Fote, 2001). However, application of FES electrodes for exercise requires experienced technicians and additional time.

Approaches to leg cycling interventions often require the utilization of FES-induced contractions in the paralytic muscles (Hasnan et al., 2012; Sadowsky et al., 2013). Adults with chronic tetraplegia and paraplegia completing up to 16 weeks of 10-30 minute FES leg cycling sessions 2-3 days each week significantly increased VO_{2peak} from 0.78 L/min to 0.95 L/min (Hooker et al., 1992). However, a change in pre- to post-training VO_{2peak} was only observed when participants performed a graded FES leg cycling stress test to fatigue (Hooker et al., 1992). The same participants also performed a voluntary arm cycling stress test to fatigue, which showed no change in peak VO_2 from pre- (1.16 L/min) to post-training (1.17 L/min; Hooker et al., 1992). Thus, the reported improvement in peak VO_2 may have been specific to the mode of exercise and not caused by central cardiovascular changes (Hooker et al., 1992). Although no comparison was performed, arm cycling stress tests clearly elicited higher peak VO_2 values and allowed greater peak power outputs (Hooker et al., 1992). Individuals with SCI participating in the combination of FES leg cycling with arm exercise, may provide greater improvements in peak aerobic capacity compared to FES leg cycling alone (Mutton et al., 1997).

The combination of FES-induced leg exercise and voluntary arm exercise has been termed “hybrid” exercise. The rationale for combining FES LE exercise and voluntary upper extremity exercise includes activation of the largest possible muscle mass, reduced lower extremity venous pooling to increase SV and Q, and training at a higher VO_2 to further improve aerobic capacity compared to either modality performed alone (Hooker et al., 1995). FES training in combination with multiple modes of exercise such as cycling, rowing, and walking have been produced (Deley et al., 2015).

A study including adult males with a range of SCI lesion levels (C5-6 to T12-L1) utilized a multi-phase program to compare FES leg cycle and FES hybrid exercise training (Mutton et al., 1997). The first training phase consisted of training with only FES leg cycling (35 sessions) and the second training phase consisted of only FES hybrid exercise (41 session; Mutton et al., 1997). Following FES leg training, VO_{2peak} was the only physiological variable to significantly increase, but only during graded FES leg cycling tests (1.29 L/min to 1.42 L/min) compared to graded arm cycling tests (1.35 L/min to 1.36 L/min; Mutton et al., 1997). Following FES hybrid training, peak VO_2 increased during graded hybrid testing (1.69 L/min to 1.91 L/min), but not during graded arm or FES leg testing (Mutton et al., 1997). Similar to Hooker et al., (1992), improvements in peak VO_2 were only evident during graded testing similar to the training (Mutton et al., 1997). In this study, hybrid exercise elicited greater peak VO_2 values compared to arm or FES leg cycling alone, which is consistent with other research (Davis, Hamzaid, & Fornusek, 2008; Deley et al., 2015; Mutton et al., 1997).

Following SCI, fewer options for aerobic exercise are available, but individuals may benefit from participating in arm cycling alone or FES leg cycling exercise. Improvements in aerobic fitness may be greater when combining UE and LE exercise. However, the combination of these modes of exercise requires additional equipment and professional assistance. Current exercise recommendations for SCI include the use of FES to assist exercise, but as for most training methods, safety should be addressed. When using FES training, several safety issues require careful monitoring. Physiotherapists should be aware of the potential for surface skin burns due to the electrodes, ankle injury, pressure or friction ulcers, autonomic dysreflexia, and fractures (Deley et al., 2015). The physiotherapist should maintain caution in using FES with patients who have partially preserved sensations in their LE as the high intensity of stimulation required to elicit movements could be painful (Sadowsky, 2001). Individuals with SCI may also consider robotic-assisted training as an alternative to electrical stimulation and arm cycling.

Robotic-Assisted Training

Robotic exoskeletons allow individuals with a SCI to maintain an upright position while partially bearing their body weight during ambulation. The robotic device takes the place of a physiotherapist, who typically manually moves the lower limbs of the patient. The exoskeleton allows stabilization of the trunk in the sagittal and lateral directions during forward movement. Stepping movements can be controlled by the individual or therapist with the use of button controls attached to the device or by the individual shifting his or her weight and center of mass to initiate stepping by the device (Kressler, Nash, Burns, & Field-Fote, 2013). However, training with robotic devices may be most beneficial during the initial stages of rehabilitation to facilitate sitting to standing maneuvers and elicit precise gait-specific proprioceptive input responsible for motor learning among those without the muscular strength to support their body weight (Field-Fote & Roach, 2011; Louie, Eng, Lam, & Spinal Cord Injury Research Evidence Research Team, 2015).

Hoekstra et al. (2013) investigated the effects of a 10 to 16 week (24 sessions) robotic gait training program on cardiorespiratory fitness in individuals with an incomplete SCI. Each robotic training session consisted of 20 to 40 minutes of walking time. Cardiorespiratory fitness was assessed during a graded arm cycling exercise test before and after the training period. Following training, there was no change in peak VO_2, but resting and submaximal HRs at a constant workload decreased (Hoekstra et al., 2013). However, cardiorespiratory fitness was only measured during graded arm ergometry tests despite the focus of training on the lower extremity musculature, which may have affected the results of this study. In another study, robotically assisted training significantly improved VO_{2peak} during a treadmill walking stress test, but not during an arm cycling stress test (Gorman, Scott, York, Theyagaraj, Price-Miller, & McQuaid, 2016). Based on these results, the improvement in peak VO_2 following robot-assisted gait training may be caused by improved muscular strength and mitochondria utilization of the lower extremities rather than improved cardiorespiratory fitness (Cheung, Ng, Yu, Kwan, & Cheing, 2017).

Fenuta and Hicks (2014) compared oxygen demand while iSCI participants walked using three different treadmill conditions with robotic assistance, without therapist assistance, and body weight support (BWS). The metabolic demand was significantly lower for treadmill walking with robotic assistance (30% of peak VO_2) compared to the two other conditions (54% of peak VO_2; Fenuta & Hicks, 2014). Based on these results, robotic treadmill walking may provide a sub-optimal intensity for cardiorespiratory improvement.

In a 12 week (5 days each week) training study, the metabolic responses to FES, manual assistance, or robotic assistance treadmill walking and over ground walking were compared (Kressler et al., 2013). Following training, peak VO_2 increased from pre-training values for all groups (0.15 ± 0.24 L/min) except the robotic assisted group (0.00 ± 0.18 L/min; Kressler et al., 2013). The authors concluded that the amount of stepping assistance provided by the robotic device limited volitional exertion to an extent that it did not provide an appropriate cardiorespiratory stimulus for improvement.

Another disadvantage of robotic exoskeleton use is the loss of muscular activation needed to support the torso, which reduces the energy expenditure during activity compared to manually assisted training with a therapist (Israel, Campbell, Kahn, & Hornby, 2006). As with BWS training, the amount of support provided by the exoskeleton needs to progressively decreased so motor function can be restored (Israel et al., 2006; Morawietz & Moffat, 2013). Those who are deconditioned during the subacute phase of injury are likely to receive more benefit and potential for training adaptation from robotic assisted stepping (Chang, Kim, Huh, Lee, & Kim, 2013; Kressler et al., 2013). Thus, walking with robotic assistance is more suitable for individuals in the initial phase of rehabilitation because they often lack the ability to perform more rigorous forms of training (i.e. overground walking).

In summary, although robotic gait training may be a beneficial approach to improving walking performance, it is unclear whether there may be beneficial adaptations for cardiorespiratory fitness. Those with SCI participating in robotic step training have shown improvements in peak VO_2 during treadmill based exertional tests, but not during exertional arm ergometry tests (Gorman et al., 2016; Hoekstra et al., 2013). These results may be due to improved muscular strength and gait performance rather than cardiorespiratory adaptations. Conversely, no changes from pre- to post-training peak VO_2 have been reported for SCI individuals participating in robotic step training (Kressler et al., 2013). Less muscular activation associated with robotic assisted walking elicits a lower metabolic cost compared to over ground walking, which may limit cardiorespiratory stress needed for beneficial adaptation (Fenuta & Hicks, 2014). Robotics training can be an effective introductory rehabilitative method, but may not be the most effective long-term method of training. The less strenuous nature of robotic training appears to be more beneficial for deconditioned individuals lacking motor function and strength for over ground walking or manually assisted and FES treadmill walking. Individuals with SCI may seek an alternative approach to achieve partial body-weight support in the water.

Underwater Treadmill Exercise

Aquatic exercise in deep or shallow water has become a popular method of training and rehabilitation because of the combined effect of buoyancy related weight reduction and the additional drag resistance to limb movement. The utility of exercise in an aquatic environment for maintaining or improving cardiorespiratory fitness in healthy, non-disabled adults has been thoroughly investigated. The body supporting effect of water in this environment also makes exercise more achievable for individuals with an orthopedic or neurological limitation. However, the utility of this environment for providing similar health benefits to those with a SCI warrants further investigation.

Due to the physical properties of water, water immersion (WI) alters physiological responses. When immersed in approximately 1 meter of water, a force equal to approximately 89 mmHg, close to expected diastolic pressure, acts on the body in a squeezing upward action (Becker, 2009). In general, WI causes blood displacement upward and subsequent increases in right atrial pressure (Becker, 2009). As water level increases, SV also increases due to this improved central blood volume and right atrial pressure (Becker, 2009; Wertheimer & Juksik, 2014). As such, Q is maintained with a lower HR. The decrease in HR may also be attributable to a diving bradycardia reflex. This occurs due to the hydrostatic pressure and buoyancy of the water which cause a higher volume of blood to be distributed to the trunk, improving conditions for blood filling during diastole, leading to increased preload (Panneton, 2013). Improving Q during exercise is particularly beneficial for those with SCI because reduced muscle pump action and sympathetic tone increases susceptibility of lower extremity (LE) blood pooling (Phillips et al., 1998). The buoyant effects of the water may also lead to altered VO_2 and energy expenditure (EE) during water treadmill walking (Alkurdi et al., 2010; Gleim & Nicholas, 1989).

Immersion depth influences weight bearing due to buoyancy (Alkurdi et al., 2010). During static conditions, immersion up to the 7^{th} cervical vertebra reduces bearing of body weight by 85% while immersion up to the anterior superior iliac spine may reduce body weight by approximately 57% (Harrison, Hillman & Bulstrode, 1992). Altering depth also alters physiological responses during movement. Gleim and Nicholas (1989) compared VO_2 and HR responses during treadmill walking and jogging in different water depths versus on land. Participants exercised at speeds between 40.2 and 160.9 m/min, which increased in 13.4 m/min increments. The effects of different immersion depths were evaluated at the lateral malleolus, just below the patella, at the mid-thigh, and approximately at the umbilicus. At speeds greater than 53.7 m/min, shallower immersion depths elicited significantly higher VO_2 and HR responses compared to immersion at the waist and on land (Gleim & Nicholas, 1989). Each underwater exercise depth required a higher metabolic cost than on land exercise, however, the metabolic cost of exercise increased with depth height until immersion at the waist (Gleim & Nicholas, 1989). As more body surface area is covered, a greater resistive force to lower extremity movement increases metabolic demand until enough of the body is submerged to partially reduce body weight.

Deep water running (DWR) requires runners to wear a buoyant vest or belt that suspends their body in the water without being able to touch the ground (Reilly et al., 2003). Runners are able to mimic the limb pattern of land-based running without ground impact. Compared to land-based running, DWR utilizing buoyancy vests typically elicits a lower maximal oxygen consumption and HR (Butts, Tucker, & Greening, 1991; Reilly, Cable, & Nevill, 2002). However, there have been other reports of similar VO_2 and HR responses between DWR and land-based running (Frangolias, Rhodes, Taunton, & Belcastro 2000). Further, LE kinematics and muscle recruitment appear to differ between DWR and land-based ambulation, while shallow water walking and running (SWR) mimics that of land-based ambulation (Silvers, Rutledge, & Dolny, 2007).

Shallow water running is performed in the shallow end of a pool with waist-high water level and mimics running on land. Compared to DWR that lacks ground contact, SWR involves a ground reaction force component and closed kinetic-chain movement similar to that of on-land ambulation. Increasing the water level will reduce ground reaction forces, while increasing the frontal resistance of forward movement in the water (Silvers et al., 2007). Like DWR, SWR has shown to produce lower maximal VO_2 and HR responses compared to land-based treadmill running (Dowzer, Reilly, Cable, & Nevill, 1999), but different immersion depths have provided contrasting results when using an underwater treadmill (Pohl & McNaughton, 2003). In contrast to DWR and SWR, running on an aquatic treadmill does not require forward movement through water and allows a more natural gait pattern (Silvers et al., 2007).

Underwater treadmill training is a method of ambulatory training on a treadmill, but in an aquatic setting. The treadmill belt moves forward or backward as an individual is required to walk against the resistance of the water, with or without supplemental jets. While submerged, water level up to an individual's xiphoid process will provide body weight support that reduces stressful ground reaction forces. When immersed, the amount of body weight support a person experiences is reliant upon the height of the water. Compared to land treadmill running, underwater treadmill running has proven to elicit greater VO_2 and HR responses (Gleim & Nicholas, 1989; Pohl & McNaughton, 2003). Exercise on an underwater treadmill can yield variable VO_2 responses due to differences in water depth, treadmill speed, and water resistance.

Alkurdi et al. (2010) compared energy expenditure, HR, and perception of effort responses to multiple treadmill walking speeds on land and in different water depths among females. Participants performed 5 minute walking sessions at six different speeds. The water depths during exercise were at the xiphoid process, 10 cm below the xiphoid process (-10 cm), and 10 cm above the xiphoid process (+10 cm). At speeds greater than 1.1 m/s, energy expenditure and HR responses at depths up to the xiphoid process were greater than on land exercise (Alkurdi et al., 2010). Small adjustments in water depth can significantly affect VO_2, which was significantly different at each 10 cm increment (Alkurdi et al., 2010). The metabolic cost of underwater walking decreased every 10 cm as the amount of body-weight support increased. Similarly, there was a greater perception of effort for underwater treadmill walking at each depth compared to land treadmill walking (Alkurdi et al., 2010). While walking, a water depth 10 cm above the xiphoid process elicited a similar VO_2 compared to land treadmill walking (Alkurdi et al., 2010).

The higher responses may be associated with the higher intensity of drag forces acting on the LE versus the trunk and the UE when partially immersed or increased ground reaction forces due to less water and buoyancy. Higher VO_2 responses may have also been due to less centrally redistributed blood at lower water levels and/or the changes in neuromuscular patterns of active muscles at different levels of body immersion (Alkurdi et al., 2010; Andersson, Liner, Fredstad, & Schagatay, 2003; Barbosa, Garrido, & Bragada, 2007). Thus, the physiological demand has been shown to be lower for deeper water depths as HR, lactate concentrations (La), and VO_2 are higher during shallow water exercise (Alkurdi et al., 2010; Pohl & McNaughton, 2003).

Similar to a land treadmill, the workload associated with underwater treadmill walking can be increased with walking speed. Buck et al. (2001) examined the effects of different water temperatures (30, 35, and 40°C) and underwater treadmill walking speeds (4, 5, and 6 km/hr) on VO_2 during 30 minutes of underwater treadmill walking. Participants completed nine sessions with a random combination of speed and temperature. Mean VO_2 and HR increased with increasing walking speed (Buck et al., 2001). While submerged to the xiphoid process, a mixed group of men and women completed nine 5-minute submaximal underwater treadmill trials at three different speeds with or without water-jet resistance compared to similar land treadmill speeds (Rutledge, Silvers, Browder, & Dolny, 2007). When there was no water-jet resistance, VO_2 responses were similar between land treadmill and underwater treadmill running speeds (Rutledge et al., 2007). Treadmill walking in an aquatic environment provides reduced weight-bearing and can elicit similar physiological responses to land treadmill walking in healthy adults without a physical disability.

Healthy, young adults running on an aquatic treadmill with jets had similar VO_2 compared to running on a land treadmill with 0% to 8% incline (Porter, Blackwell, Smith, Wagner, & Gordin 2014). Further, peak treadmill tests on both aquatic and land treadmills produced similar values for VO_2, respiratory exchange ratio, ratings of perceived exertion (RPE), exercise speeds and exercise durations with healthy, young, adult men (Silvers et al., 2007). Thus, keeping water level at the xiphoid process and using water jets to mimic the resistance produced by increasing treadmill incline on above ground treadmills, produces similar workloads and physiological responses to that of a land treadmill (Porter et al., 2014; Silvers et al., 2007; Stevens & Morgan, 2015). Therefore, underwater treadmill training (UTT) may be a mode of exercise beneficial to improving cardiorespiratory fitness in those with diminished physical function compared to above ground walking. Particularly for individuals with a SCI, UTT may have additive benefits compared to out of water treadmill walking with a harness.

Underwater Treadmill Training for Individuals with SCI

Walking in water will provide a buoyant force on the LE allowing easier movement for individuals with a SCI that have a higher level of impairment. The buoyancy of the aquatic environment reduces the compressive forces placed on the joints during exercise, which is especially beneficial for individuals with gait irregularities or contraindications for land-based walking. Less reliance on restrictive body harnesses and straps is also available while immersed due to the lower gravitational forces (i.e. more body weight support). Similarly, those with less LE strength/force development are capable of better lower limb movement due to reduced gravitational pull on the impaired lower limbs. The aquatic environment may allow individuals with SCI to voluntarily move their LE, which is often absent during above ground walking (Dolbow, Gassler, Dolbow, & Stevens, 2016). In comparison to the lower resistance of air during land-based walking, the velocity dependent water resistance associated with submerged walking is capable of improving the strength of active musculature and gait performance (Stevens, Caputo, Fuller, & Morgan, 2015). Several researchers who worked with able-bodied samples reported cardiorespiratory benefits and examined metabolic costs associated with UTT. However, research is lacking for the metabolic demand of UTT and the potential for improving cardiorespiratory fitness among SCI individuals.

In the limited data available, among those with a SCI, improvements in cardiovascular parameters have been reported following 8 weeks of UTT (Stevens & Morgan, 2015). Training consisted of three walks per session for three sessions each week. Each walking bout lasted 5 minutes during the first two weeks of training and increased by 1 minute every 2 weeks after. Initial treadmill walking speed corresponded to a HR slightly greater than resting or a rating of perceived exertion of at least 3. Treadmill walking speed progressed 10% biweekly. Following training, participants experienced a 7% to 17% decrease in mean exercise HR (Stevens & Morgan, 2015). Lacking a metabolic measurement, an improvement in submaximal exercise HR may indicate positive cardiorespiratory adaptation. In a 6-week study involving individuals with subacute stroke, UTT was compared to cycle ergometer exercise (Han & Im, 2018). Following training, the UTT group exhibited significant improvements in peak VO_2, HR, and symptom-limited exercise tolerance test duration (Han & Im, 2018). Further, the UTT group experienced greater improvements in peak VO_2 compared to the cycling exercise group (Han & Im, 2018).

There is potential for treadmill training in an aquatic environment to be an appropriate training modality benefiting cardiovascular fitness and gait performance for those with SCI (Stevens & Morgan, 2015). Water is capable of retaining heat and heat transfer from the body can occur up to 25 times faster than air (Becker, 2009). For these reasons, the rehabilitative use of water is versatile across a wide range of temperatures (Becker, 2009). A water temperature range of 33.5-35.5°C is common for many therapeutic pools that allows long immersion durations and exercise without chilling or overheating (Becker, 2009). Although few studies exist, exercise in a water temperature up to 35°C has been shown to be safe and feasible for those with SCI (Stevens et al., 2015; Stevens & Morgan, 2015). Passive hot water (39°C) immersion for upwards of 60 minutes has shown both the rate of increase and maximum elevation of core temperature to be similar between tetraplegic and able-bodied individuals (Leicht et al., 2015). However, core temperature recovered more slowly in those with SCI (Leicht et al., 2015). Still, SCI individuals may warrant closer monitoring during warm water immersion due to potential heat storage complications. The warm temperature of water used during UTT, which is below resting core temperatures, may help lessen muscle spasticity and muscle tonicity, thus may be a more ideal exercise environment for those with SCI (Dolbow et al., 2016).

In summary, SCI reduces an individual’s functional capacity for exercise and often leads to increased risk for cardiovascular disease. Dysfunction of the ANS and loss of motor control requires access to specific adaptive modalities for proper aerobic exercise participation recommended to reduce cardiovascular disease risk factors. Functional electrical stimulation involving both the UE and LE can produce greater improvement of cardiorespiratory fitness measures compared to either alone. However, it is uncertain when reports of improved peak VO_2 or submaximal exercise HR are due to central or peripheral adaptations. However, the combination of these modes of exercise requires additional equipment and professional assistance for FES application and monitoring of the participant. Robotic devices provide body weight support during ambulation and replace manual manipulation of the LE by a physiotherapist during walking. However, training using robotic assistance tends to lack intensities high enough to stimulate improvements in cardiorespiratory fitness. Use of these devices may be more suitable for deconditioned individuals in the rehabilitative stage shortly after SCI.

Treadmill walking in water depths from the ankle to the chest elicits similar or higher peak VO_2, HR, and RPE compared to land treadmill walking. At these water depths, the buoyant effects of water is not greater than the necessary energy to overcome the resistance of water. In particular, underwater treadmill walking up to the xiphoid process can provide adequate cardiovascular stimulus with additional body-weight supporting benefits in healthy non-disabled adults. As such, UTT may be a beneficial mode of exercise for improving cardiovascular fitness in those with SCI.

Cardiorespiratory Fitness Testing

An individual's maximal or peak oxygen uptake ($VO_{2max/peak}$) is considered to be the best representation of his/her peak physical capacity (Armstrong & Welsman, 2007). Valid assessment of VO_{2max} requires maximal exercise testing. Maximal exercise testing can vary between incremental, intermittent, and constant load protocol designs (Eerden, Dekker, & Hettinga, 2018). Incremental and constant load tests are considered to be continuous as both are performed until physical exhaustion or test termination criteria are reached. Protocols for incremental exercise testing are designed to increase the physical workload incrementally in successive stages until volitional exhaustion or termination criteria are reached by the participant. Intermittent maximal exercise tests provide participants with a resting period between stages.

Traditionally, maximal exercise tests determine whether an individual achieved a true VO_{2max} if the individual achieves a plateau in VO_2 with increasing external workload. If a plateau in VO_2 could not be established, secondary criterion may be used for determining a VO_{2peak} such as achieving an RER $\geq$ 1.10-1.15 or the individual's age-predicted maximum HR (Edvardsen, Hem & Anderssen, 2014). However, those with SCI may not achieve a VO_{2max} based on these criteria due to cardiovascular disruption of the autonomic nervous system, reliance upon relatively smaller muscle or muscle groups, impaired pulmonary function causing lower ventilatory capacity, and/or cardiovascular medications limiting the rise in HR (Sisto & Evans, 2014). Volitional exhaustion or inability to maintain a required load or speed have also been used as criteria for determining true maximal exertion in healthy and SCI populations (Eerden et al., 2018). A VO_{2peak} is considered to be achieved when VO_{2max} criteria are not established for testing protocols or participants successfully complete a maximal exertion test but fail to achieve the established criteria (Eerden et al., 2018). According to the American College of Sports Medicine, VO_{2peak} is considered to be the gold standard for determining a person's peak physical capacity (Eerden et al., 2018).

For individuals with a SCI, a treadmill or upper and lower body cycle ergometers are common modalities used for conducting exercise tests. Motor-driven treadmills on land allow incremental increases in speed and/or incline, while underwater motor-driven treadmills allow the adjustment of speed and water jet resistance rather than incline. Comparisons of maximal exercise testing involving either a land or water based treadmill have been conducted among healthy adults (Choi et al., 2015; Greene, Greene, Carbuhn, Green, & Crouse, 2011; Schaal, Collins, & Ashley, 2012; Silvers et al., 2007). Although, maximal exercise testing using an underwater treadmill in those with a SCI has yet to be investigated.

Silvers et al. (2007) tested collegiate runners in a randomized order using two continuous, incremental peak VO_2 protocols for underwater treadmill running and land treadmill running. For both protocols, running speed was initially set at each participant's preferred speed and increased 13.4 m/min (0.5 mph) every minute for 4 minutes after which either jet resistance or treadmill incline was increased every minute until volitional exhaustion. The UT protocol began with 40% water jet resistance until completion of the first 4 minutes, then incrementally increased 10% every minute until volitional exhaustion. The land treadmill protocol began at the initial predetermined running speed and 0% incline. Following completion of the first 4 minutes, the incline increased by 2% every minute until volitional exhaustion. Ventilatory measures, VO_2, HR, and respiratory exchange ratio were measured continuously during testing. To determine peak values for breath-by-breath variables, four 15 second samples around the highest 15 second VO_2 sample were averaged and used for analysis. The UT protocol elicited greater ventilation and breathing frequency values, but VO_2, HR, respiratory exchange ratio, speed, and exercise durations were similar between protocols (Silvers et al., 2007). Thus, maximal exertion testing using an underwater treadmill may provide similar peak cardiorespiratory measures and testing durations compared to the land treadmill among healthy men and women (Silvers et al., 2007).

Another study comparing peak cardiorespiratory responses during land-based treadmill and UT running replicated the UT incremental exercise test protocol of Silvers et al. (2007; Schaal et al., 2012). The land-based treadmill protocol used a self-selected, moderately vigorous pace that remained constant throughout the entirety of the test. Every 2 minutes, treadmill grade was increased by 2% until volitional exhaustion. Respiratory exchange ratio and VO_2 were continuously assessed during testing. Maximal VO_2 was considered as the highest VO_2 value achieved. Using the Borg 6-20 scale, RPE was assessed every 2 minutes. Respiratory exchange ratio, VO_2, and RPE were similar between the land-based and the UT running protocols (Schaal et al., 2012). However, HR was greater during the land-based treadmill running, which is consistent with other studies due to the effect of the hydrostatic pressure of water (Schaal et al., 2012). Thus, a continuous multistage protocol may be appropriate for testing peak cardiorespiratory measures among healthy adults (Schaal et al., 2012; Silvers et al., 2007).

Greene et al., (2011) assessed cardiorespiratory responses during incremental exercise tests using an UT and land-based treadmill among healthy men and women using an incremental Bruce protocol. Following a brief warmup, treadmill speed began at 2 mph and incrementally increased by 1 mph for six 3 minute stages. Tests continued until either the participant requested to stop or completion of the final stage. Land treadmill grade was constant at 0%, while 5 different jet resistance testing conditions (0%, 25%, 50%, 75%, 100%) were used. Water depth for UT testing was set up to the fourth intercostal space such that approximately 75% of weight loss was achieved.

During testing, VO_2 was continuously measured, while HR and RPE were assessed during the last 30 seconds of each exercise stage. The highest VO_2 achieved was considered maximal.

Treadmill speed and water resistance greatly affected cardiorespiratory responses (Greene et al., 2011). At similar treadmill speeds up to 3 mph, the UT protocol elicited greater VO_2 responses when participants were exercising at 75% and 100% water jet resistance (Greene et al., 2011). At treadmill speeds of 5 and 6 mph, the UT protocol elicited greater VO_2 responses only at 100% water jet resistance (Greene et al., 2011). When the treadmill speed was set up to 3 mph, the UT protocol was shown to elicit a similar VO_2 response without water jet resistance (Greene et al., 2011). When water jet resistance was set to 0% and 25%, HR values were similar or slightly lower at similar land and aquatic treadmill speeds (Greene et al., 2011). Water jet resistances greater than 25% resulted in higher HR values (Greene et al., 2011). This study showed that the UT protocol elicited similar or greater VO_2 responses depending on the amount of water resistance created by the addition of jet propulsion forces. In particular, jet resistances between 75% and 100% caused the greatest impact on VO_2 responses (Greene et al., 2011). More notably, treadmill speeds of 3 mph elicited similar VO_2

Miller, Dougherty, Green, and Crouse (2007) compared cardiorespiratory responses of moderately trained men and women when performing a standard Bruce protocol or modified Astrand treadmill protocol. The authors found participants achieved similar VO_{2max} values between both protocols (Miller et al., 2007). However, the Bruce protocol required a significantly longer treadmill time to achieve maximal volition (Miller et al., 2007). The modified Astrand protocol, however, elicited greater maximal

HR values (Miller et al., 2007). These results indicate that Bruce and Astrand maximal exertion protocols are applicable to eliciting maximal cardiorespiratory responses among healthy men and women when exercising on either land or aquatic treadmills.

Each of these UT studies utilized a water depth up to the chest (Greene et al., 2011; Schaal et al., 2012; Silvers et al., 2007). As previously mentioned, water depths greater than waist height has been shown to decrease the metabolic demand of exercise due to water buoyancy counteracting the effects of gravity. However, the use of water jet resistance is capable of increasing metabolic demand due to additional forces on the movable extremities. Further, treadmill speeds used for maximal testing began at or above 2 mph (54 m/min). The modified Astrand protocols began with treadmill speeds dependent upon participant's preferred running speed, which may be more suitable for those with limited walking ability (i.e. a SCI). Depending on the level and time since injury, walking speeds for SCI interventions and functional capacity testing are often below 54 m/min (Field-Fote & Roach, 2011). Previously, speeds of at least 12 m/min have been used for individuals with SCI participating in UT training (Stevens et al., 2015). Thus, it may be reasonable that individuals with a SCI may walk on a UT at speeds up to 54 m/min.

Treadmill incremental exercise tests progressively increase the work rate as either speed or incline to increase the cardiopulmonary stress to the participant. However, those with SCI have a limited range of attainable speeds and incline due to a reduced exercise capacity compared to healthy able-bodied individuals. As such, maximal exercise testing protocols for individuals with a SCI have utilized both incremental and constant work rates (Jack, Allan, & Hunt, 2009; Jack, Purcell, Allan, & Hunt, 2010; Jamieson, Hunt, &

Allan, 2008). Special consideration involving protocol selection is warranted for those with gait and exercise limitations. For incremental exercise testing, a low initial metabolic rate with small to moderate individual progressive increments has been recommended for those with SCI (Eerden et al., 2018; Jamieson et al., 2008). Previously, such increments in workload were achieved by increases in either speed or grade during treadmill testing or increases in resistance during arm and leg cycling ergometry. Also, device or therapist assistance may be needed depending on the severity or level of injury, however, the body weight reduction provided during underwater treadmill walking may serve as a more feasible mode of exercise testing. The utility of the underwater treadmill as a maximal exercise testing modality has yet to be researched for those with chronic SCI.

Conclusions

Following SCI, individuals are subject to physical and physiological consequences that can negatively affect physical activity performance. Regular participation in aerobic exercise is recommended to reduce the risk of developing cardiovascular disease and improve functional capacity. Limitations in muscular and neurological function below an individual's level of lesion is hindering to the availability of exercise modalities and VO_{2Max} available to these individuals. Underwater treadmill training has currently become a method of training for those with SCI, however, the cardiorespiratory response for these individuals to this type of exercise has not been tested. Underwater treadmill walking is a practical modality for those with SCI as it allows the use of the lower and upper body musculature without heavy reliance upon professional equipment (i.e. body harnesses, FES or robotic devices) or assistance.

Further, the buoyancy of the aquatic environment assists body weight support and normal gait, while water resistance is capable of strengthening the deconditioned lower body musculature of those with SCI.

The best representation of an individual's aerobic capacity has been VO_{2Max}. Selection of mode and protocol can have variable effects on VO_{2Max} results during testing (Armstrong & Welsman, 2007). It is known that UT exercise provides adequate cardiorespiratory stimulus for the able-bodied population; however, the metabolic demand of this training method has yet to be assessed in those with SCI. Further, the maximal aerobic exercise testing has yet to be conducted using the underwater treadmill among those with SCI. The purpose of the first study is to examine the cardiorespiratory responses to underwater treadmill walking of adults with and without SCI. Secondly, we sought to examine a VO_{2Max} testing protocol based on target RPE among this population in comparison with age- and sex-matched able-bodied individuals.

CHAPTER III

METABOLIC COST OF UNDERWATER TREADMILL WALKING IN INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

Introduction

Incomplete spinal cord injury (iSCI) can result in interrupted neural communication between higher brain centers and distal sensory-motor neurons (Jacobs & Nash, 2004). This neurologic damage can result in diminished sensation, autonomic nervous system function, and motor performance below the level of the lesion, making it more difficult to accumulate sufficient aerobic physical activity (Castro, Apple, Staron, Campos, & Dudley, 1999; Jacobs & Nash, 2004). For those with iSCI who have retained arm function, upper body aerobic exercise is recommended, but the onset of upper extremity fatigue can limit any training effect (Warburton, Eng, Krassioukov, & Sproule, 2012). When possible, the inclusion of the larger, lower body musculature during aerobic exercise may allow greater physiological benefits for individuals with iSCI.

Aquatic exercise has become a popular method of training and rehabilitation. This mode of exercise has been associated with improved cardiovascular and muscular fitness, reduced musculoskeletal stress, and improved stability during ambulation among the able-bodied population (Becker, 2009). A submerged treadmill allows control of walking speed and water depth, temperature, and resistance via jet propulsion. Water buoyancy supports the body during exercise while drag resistance to limb movements strengthens active muscles (Becker, 2009). Further, hydrostatic pressure promotes venous return to the heart and central blood volume accumulation (Panneton, 2013). These features of the aquatic environment may be especially useful to individuals with an iSCI.

Although several studies exist on the cardiovascular effects of water immersion at rest and during exercise for healthy adults, the utility of underwater treadmill walking for those with iSCI remains understudied. Stevens and Morgan (2015) have demonstrated the efficacy of underwater treadmill walking with individuals who have an iSCI. They reported adults with iSCI completing 8 weeks of underwater treadmill training (UTT) at progressively increasing speeds had up to a 17% decrease in submaximal exercise heart rate. However, the metabolic cost of individuals with iSCI performing underwater treadmill walking has not been studied. In order for underwater treadmill walking to be a safe and effective form of exercise and rehabilitation for this population, it is important to understand the metabolic and cardiorespiratory demand of this mode of activity. Thus, the purpose of this study was to compare the VO_2 associated with walking at speeds of 0.50 and 0.75 mph in the underwater treadmill in addition to the cost of self-selected speeds based on specific ratings of perceived exertion (RPE) for people with iSCI. Secondly, the cardiorespiratory responses of the adults with iSCI were compared to individuals without iSCI of similar sex and age to determine if heart rate (HR) and oxygen consumption (VO_2) differed. Finally, the average reported speed selected at each RPE was examined amongst those with and without iSCI.

Methodology

Participants

Apparently healthy adult males with iSCI ($n = 4$) and age-matched males without spinal cord injury ($n = 4$) volunteered to participate in this study. Inclusion criteria for those with iSCI were age between 20-65 years and being more than 1-year post-injury with a lesion at T7 or below (Grigorean et al., 2009; Hector, Biering-Sorensen, Krassioukov, & Biering-Sorensen, 2013). Participants with an iSCI provided physician documentation of their SCI and American Spinal Cord Injury Impairment Scale (AIS) rating and provided medical clearance to engage in laboratory testing. Descriptive data for participants are presented in Table 1. Participants without iSCI were included in the study if they were ages 20-65 years old and did not require medical clearance to participate in vigorous intensity exercise. Those without iSCI were screened using the American College of Sports Medicine (ACSM) health screening algorithm (American College of Sports Medicine, 2018). This research study was approved by the university Institutional Review Board (see Appendix A) and participants provided informed written consent prior to commencement of data collection.

Instrumentation

Anthropometric measurements

Body mass was measured in light clothing without shoes on a wheelchair scale (Seca 674, Hamburg, Germany) to the nearest tenth of a kilogram. Those in a wheelchair were weighed in the wheelchair and then the mass of the chair was subtracted to obtain the mass of the individual. For those with a iSCI who were able to maintain a fully upright position and those without a iSCI, height was measured, without shoes, to the nearest tenth of a centimeter using a standard stadiometer. For those with an iSCI who could not stand fully upright, height was measured in the supine position to the nearest tenth of a centimeter using a tape measure. Measurements were made from the top of the head to the bottom of the heel. If complete knee extension could not be achieved, segmental measurements were made and summed.

Oxygen consumption

Oxygen consumption was measured via an Oxycon portable VO_2 system (Jager, Wurzburg, Germany). Gas calibration (environmental settings and gas-analyzer calibration) was performed at the beginning of every testing day. This process included

Table 1

Descriptive Characteristics of Study Participants (N = 8)

	Group	
Variable	iSCI (*n* = 4)	Non-iSCI (*n* = 4)
Age (years)	49.8 ± 3.9	50.0 ± 7.2
Body mass (kg)	92.0 ± 14.0	86.8 ± 11.9
Height (cm)	180.1 ± 3.6	175.4 ± 14.2
Years since injury	9.4 ± 4.3	--

Note. Values are means ± *SD*. iSCI = incomplete spinal cord injury.

a 15 minute system warm-up. Both high and low gas ranges were used for calibration (O_2 = 21%, CO_2 = 5%, and O_2 = 16%, CO_2 = 0.04%, respectively).
Automatic volume calibration and calibration of the O_2 and CO_2 analyzers were rechecked prior to each testing session.

Heart rate

Heart rate was measured with a Polar heart rate monitor (Polar Electro Inc., Lake Success, NY). This device was secured around the chest of each participant approximately at the height of the xiphoid process.

Procedures

Each participant reported to the lab for two sessions. On the first day, they read and signed the informed consent, provided medical clearance (for those with iSCI) and completed the ACSM Algorithm Screening to assure medical clearance was not required (for those without SCI; ACSM, 2018). Upon completion of paperwork and anthropometric measurements, participants donned a fitted mask (Hans Rudolph, Shawnee, Kansas) for gas collection and the HR monitor. Participants remained seated and were provided 5 minutes to become accustomed to wearing the mask and HR monitor. This included adjustment of equipment and practice breathing while wearing the mask.

Participants then accommodated to walking in the underwater treadmill (HydroWorx, Middletown, PA). The temperature of the water was set to 92° F. Participants entered the foyer of the underwater treadmill which then filled with water. Participants in a wheelchair transferred from their wheelchair onto a platform in the foyer. Once the foyer was filled with water, participants moved onto the treadmill belt.

Participants were allowed to support themselves on the arm rests on the sides of the inner tank, if needed. The water level was adjusted to approximately the xiphoid process when the participant was upright in the water. When the participant was ready, treadmill speed was adjusted to 0.5 mph. After 3 minutes of walking at this speed, treadmill speed was increased to 0.75 mph and maintained for another 3 minutes. Next, the treadmill speed was adjusted, if needed, until the participant perceived his overall effort was approximately a 3 on a 1-10 rating scale, with 10 being maximal effort (Utter et al., 2004). Participants were asked to maintain an exertion level equivalent to an RPE of 3 to the best of their ability for 3 minutes. This process was repeated two more times, so that RPE ratings of 5 and 7 were achieved, consecutively. The speed of the treadmill was not visible to participants to avoid any effect it may have had on their perception of effort. Following the third minute of the final stage (at RPE of 7), participants were allowed to continue walking at a preferred speed as a cool-down until they were ready to exit the UT. Participants reported back to the lab within 7 days to repeat this protocol. All participants were instructed to avoid strenuous exercise during the 48 hours prior to this second day of testing. During testing, HR and VO_2 were continuously recorded. The HR and VO_2 recorded at the end of the third minute for each intensity were used for analysis.

Statistical Analyses

Statistical Package for Social Sciences 26.0 (Chicago, IL) software program was used for statistical analysis of data. Descriptive statistics are reported as means ± standard deviation. Statistical significance was set at $p < .05$ for all analyses. All reported values for physiological measures are expressed as mean ± standard error. Independent samples *t* tests were used to compare iSCI and non-iSCI with respect to HR and VO_2 at researcher determined speeds of 0.5 mph and 0.75 mph as well as at participant chosen RPEs of 3, 5, and 7. The test results are reported as 95% confidence intervals. One-way repeated measures ANOVAs were used to compare HR among the treadmill conditions (0.5 mph, 0.75 mph), HR among the RPE conditions (RPE3, RPE5, RPE7), VO_2 among the treadmill conditions (0.5 mph, 0.75 mph), and VO_2 among the RPE conditions (RPE3, RPE5, RPE7) for the iSCI group. Similar analyses were conducted for the non-iSCI group.

Results

Physiological responses

There were no significant differences between groups for VO_2 when walking at speeds of 0.5 and 0.75 mph, $t(6) = 0.66$, $p = .53$ and $t(6) = 0.39$, $p = .71$, respectively. There were no significant differences between groups for HR when walking at speeds of 0.5 and 0.75 mph, $t(6) = 0.93$, $p = .39$ and $t(6) = 0.82$, $p = .44$, respectively. The mean HR and VO_2 responses to underwater treadmill walking at each exercise intensity are in in Table 2.

Follow-up analyses for those with iSCI showed that there was not a significant difference in HR or VO_2 for the 0.5 and 0.75 mph conditions, $F(1, 3) = 1.37$, $p = .326$, $\eta_P^2 = .314$ and $F(1, 3) = 0.11$, $p = .759$, $\eta_P^2 = .036$, respectively. Those without iSCI also indicated no differences in HR or VO_2 for the 0.5 and 0.75 mph conditions, $F(1, 3) = 2.24$, $p = .231$, $\eta_P^2 = .428$ and $F(1, 3) = 6.99$, $p = .077$, $\eta_P^2 = .700$, respectively.

Table 2

Physiological Data by Speed

Measure	Speed	Group	*M*	*SD*	Mean Difference	95% Confidence Interval of the Difference	
						Lower	Upper
VO_2	0.5 mph	iSCI	6.44	1.17	0.41	-1.10	1.93
		Non-iSCI	6.03	0.42			
VO_2	0.75 mph	iSCI	6.31	1.63	-0.36	-2.62	1.91
		Non-iSCI	6.67	0.88			
HR	0.5 mph	iSCI	88.88	15.96	10.63	-17.30	38.55
		Non-iSCI	78.25	16.32			
HR	0.75 mph	iSCI	91.13	17.60	10.50	-20.86	41.86
		Non-iSCI	80.63	18.63			

Note. *N = 4 per group*. HR = heart rate; VO_2 = oxygen consumption; iSCI = incomplete spinal cord injury.

Between group comparisons were not significantly different for HR at RPE 3, RPE 5, and RPE 7, $t(6) = 0.49$, $p = .64$ and $t(6) = 0.67$, $p = .52$ and $t(6) = 1.56$, $p = .17$, respectively. Between group comparisons for VO_2 were not significantly different at RPE 3 and RPE 5, $t(6) = 1.17$, $p = .29$ and $t(6) = 2.70$, $p = .08$, respectively. There was a significant difference in mean VO_2 responses at RPE 7, $t(6) = 2.70$, $p = .04$. See Table 3.

Follow-up analyses for those with iSCI showed that there was not a significant difference in HR or VO_2 for the RPE conditions, $F(2, 6) = 3.33$, $p = .106$, $\eta_P^2 = .526$ and $F(2, 6) = 3.13$, $p = .117$, $\eta_P^2 = .511$, respectively. Those without iSCI had differences in HR and VO_2 for the RPE conditions, $F(2, 6) = 39.27$, $p < .001$, $\eta_P^2 = .929$ and $F(2, 6) = 93.86$, $p < .001$, $\eta_P^2 = .969$, respectively. Sidak pairwise comparisons indicated HR and VO_2 differed for all three RPE conditions.

Treadmill speeds

There was not a significant difference between groups for self-selected treadmill speeds at RPE 3, RPE 5, and RPE 7, $t(6) = 0.26$, $p = .80$ and $t(6) = 0.52$, $p = .62$ and $t(6) = 1.35$, $p = .23$, respectively. See Table 3. Follow-up analyses for those with iSCI showed that there was a significant difference between treadmill speeds selected between each RPE level, $F(2, 6) = 8.01$, $p = .02$, $\eta_P^2 = .727$. Sidak pairwise comparisons, however, were nonsignificant. For the participants without iSCI, there was a significant difference between self-selected treadmill speeds at each RPE level, $F(2, 6) = 19.88$, $p = .002$, , $\eta_P^2 = .869$. Sidak pairwise comparisons indicated treadmill speeds were significantly higher at RPE 5 and RPE 7 than at RPE 3.

Table 3

Physiological Data and Speed by RPE

Measure	RPE	Group	*M*	*SD*	Mean Difference	95% Confidence Interval of the Difference Lower	Upper
HR	3	iSCI	101.88	15.32	5.63	-22.63	33.88
		Non-iSCI	96.25	17.28			
HR	5	iSCI	107.63	20.01	-8.00	-36.90	20.90
		Non-iSCI	115.63	12.55			
HR	7	iSCI	120.00	31.54	-25.00	-64.13	14.13
		Non-iSCI	145.00	5.29			
VO_2	3	iSCI	9.06	6.19	-3.75	-11.59	4.09
		Non-iSCI	12.81	1.65			
VO_2	5	iSCI	11.31	8.15	-9.14	-19.76	1.49
		Non-iSCI	20.45	3.00			
VO_2	7	iSCI	**12.99**	10.58	**-15.41***	**-29.40**	**-1.43**
		Non-iSCI	**28.40**	4.34			
Speed	3	iSCI	1.74	1.61	-0.21	-2.19	1.77
		Non-iSCI	1.95	0.08			
Speed	5	iSCI	2.49	1.82	-0.48	-2.71	1.76
		Non-iSCI	2.96	0.14			
Speed	7	iSCI	2.93	2.16	-1.60	-4.51	1.31
		Non-iSCI	4.53	0.99			

Note. N = 4 per group. RPE = rating of perceived exertion; HR = heart rate; VO_2 = oxygen consumption; iSCI = incomplete spinal cord injury. * = significantly different between groups.

Table 4

Individual Self-Selected Treadmill Speeds at each RPE

	Treadmill Speed (mph)				
Group	RPE 3	RPE 5	RPE 7	AIS rating	Age (years)
iSCI	1.10	2.45	3.00	A	55
	0.95	0.95	1.25	C	50
	0.75	1.50	1.50	B	48
	4.15	5.05	5.95	D	46
Non-iSCI	1.95	2.95	4.25		60
	2.05	2.80	3.65		49
	1.95	2.95	5.95		48
	1.85	3.15	4.25		43

Note. iSCI = incomplete spinal cord injury; RPE = rating of perceived exertion; AIS = American Spinal Cord Injury Impairment Scale.

Discussion

This study was designed to characterize the cardiorespiratory demand of underwater treadmill exercise for those with iSCI and compare these results to sex and age-matched control participants without iSCI. Due to a lack of research and variability of physical limitation following an iSCI, the intensity of exercise during UT exercise was regulated by perceived exertion rather than predetermined treadmill speeds. This design intended to allow the achievement of progressive exercise intensities among those with a range of ambulatory limitations.

This study showed that underwater treadmill walking elicits increases in VO_2 among those with iSCI. This shows that walking at low speeds in an UT is capable of eliciting VO_2 responses above the accepted resting value of 3.5 mL/kg/min. There was not a significant difference in VO_2 and HR responses between groups when walking at these speeds. However, there was a trend for a higher mean HR among the iSCI group at both speeds. In fact, the reported RPE when walking at these speeds was lower for those without iSCI (RPE: 1) than those with iSCI (RPE: 2-3). These speeds were similar to those used for locomotive training involving treadmill-based training with manual assistance or stimulation, overground training with stimulation, and treadmill-based training with robotic assistance (Field-Fote & Roach, 2011). In comparison to these methods of locomotor training, exercise in an UT limits complications with patient transfers, body support equipment, and therapist assistance.

There was a large range of individual VO_2 responses at each exercise intensity. When excluding the AIS D participant, there were two participants with linear increases in VO_2 and intensity, which showed a close range in VO_2 responses at RPE 3 (6.95 to 7.3

mL/kg/min) and RPE 5 (8.45 to 9.4 mL/kg/min; see Table 5). Among these 2 participants, there appeared to be a larger range of VO_2 responses at RPE 7 (8.6 to 12.2 mL/kg/min). Further, the average VO_2 achieved by these 2 participants at each increasing intensity were 1.75, 2.21, and 2.52 times greater than resting VO_2 values, respectively. One participant (AIS D) achieved VO_2 values that were 4.31, 5.51, and 6.79 times greater than rest at each intensity, respectively. These data show that those with iSCI are capable of increasing energy expenditure well above resting values when participating in UT exercise. Individuals with iSCI have been reported to exhibit similar values for submaximal arm cranking (Collins et al., 2010). However, this information should be interpreted carefully due to the low sample sizes in each study and wide ranges of SCI classification compared.

For a wide range of individuals with SCI (C_7 to L_4) absolute VO_2 (mL/min) has been shown to range from 560 to 1500 during various submaximal exercises including arm crank ergometry (ACE), functional electrical stimulation in addition to leg-cycling (FES-LCE), ACE+FES-LCE, and hybrid exercise (Collins et al., 2010; Hasnan et al., 2013). In the current study, the average absolute oxygen uptake ranged from 704 to 982 mL/min. Hoekstra et al. (2013) demonstrated that previously untrained iSCI individuals with AIS C and D (N =10) are capable of achieving similar values during submaximal (750 mL/min) and maximal (1,163 mL/min) ACE. This indicates that the UT is capable of eliciting similar absolute exercise intensities as other modalities.

Interestingly, there was not a significant difference in VO_2 between those with and without iSCI when exercising at self-selected treadmill speeds for an RPE of 3 and 5. Although there was not a significant difference in the speeds selected at each intensity, iSCI participants with an AIS Impairment ratings of A, B, and C self-selected speeds below the lowest speed of the entire non-iSCI group at each respective RPE intensity. This suggests that prescribing exercise intensities using RPE rather than workload for UT training might be more appropriate. Even though they are supported by the water, these individuals (AIS A, B, C) provided additional body support by leaning on the railing of the UT. In contrast, those without iSCI did not need to lean on the railing. Thus, RPE and VO_2 could have been affected by those with iSCI providing additional mechanical body support that equates to faster treadmill speeds among those without iSCI. In contrast, a significant group difference in VO_2 at RPE 7 indicates that those with iSCI tend to be limited in exercise capacity due to a lack of recruitable musculature (Jacobs & Nash, 2004). This was evident as there were much smaller increases in self-selected speeds across RPE intensities among those with iSCI versus those without iSCI.

The self-selected speeds at an RPE of 3 ranged between 0.75 and 1.10 mph for all but one iSCI participant (AIS D) who self-selected a speed of 4.15 mph. This participant (AIS D) self-selected higher speeds at RPE 3, RPE 5, and RPE 7 than each non-iSCI participant. The self-selected speeds at moderate (RPE 5) to high intensities (RPE 7) UT exercise appeared to have a wider range for those with iSCI (Table 3). In comparison, those without iSCI self-selected a wider range of treadmill speeds at RPE 7 compared to RPE 3 and RPE 5 (see Table 3).

To our knowledge, this is the first study to show that those with iSCI can regulate UT exercise workloads based on RPE to elicit linearly increasing HR responses. However, there were variable HR responses at each RPE among those with iSCI. The HR and VO_2 nearly remained the same for one participant with iSCI (AIS B) across each

RPE intensity. Further, the HR responses for one individual with iSCI (AIS D) and his age-matched participant without iSCI appeared more similar at RPE 5 (117 vs 115 bpm) and RPE 7 (153 vs 140 bpm). Among those with iSCI and a linear increase in HR, the average $\%HR_{Max}$ at RPE 3, 5, and 7 was 64.3%, 66.8%, and 77.4%, respectively. This was calculated using the age-estimated max HR formula 208 – (age x 0.7). According to the ACSM, persons with chronic diseases or disabilities are recommended to participate in cardiorespiratory activity within an intensity range of 50-80% of an individual's peak HR (Figoni, 1997). Thus, individuals with iSCI are capable of safely selecting exercise intensities via RPE that satisfy the recommendations for cardiorespiratory activity.

Arm cranking is a common and feasible method of prescribing cardiorespiratory exercise for those with SCI (Jacob & Nash, 2004). However, arm ergometry is associated with a lack of translational application to wheelchair mobility (Jacobs & Nash, 2004). Wheelchair propulsion on a treadmill is a method that can be used to test cardiorespiratory fitness of those with SCI, but it is unknown whether a standardized or personal chair should be used (Jacobs & Nash, 2004). Individuals with SCI may also participate in cardiorespiratory training via modalities involving functional electrical stimulation (FES), which requires specific professional operation. However, this study shows that the UT is a feasible method for prescribing cardiorespiratory exercise that limits the use of supportive devices and therapist assistance. Further, the UT has the advantage of allowing individuals to maintain an upright, low load-bearing position and requires the individual to mimic walking. According to Stevens, Caputo, Fuller and Morgan (2015), 8 weeks of UT training improved lower extremity strength and gait performance among 11 individuals with iSCI. Thus, the UT offers the advantage of providing adequate cardiorespiratory stress and simultaneous locomotor training.

A limitation of this study was a low sample size. More participants may have allowed differences in statistical analyses. Another limitation of this study was that individuals with walking impairments and sensory loss may have an altered perception of effort, which may have subsequently affected physiological comparisons at individual RPE intensities. However, prescribing exercise via RPE is often more feasible than traditional methods since calculating physiological estimations, preliminary testing, and equipment such as HR monitors are not necessary. For able bodied individuals, ambulatory exercise can be prescribed more easily given there is a wide range of workloads that may be achieved from low to high intensity exercise. However, individuals with gait, autonomic and exercise capacity limitations are often subject to more narrow ranges of workloads across these exercise intensities. Further, those with iSCI may have autonomic dysfunction affecting their HR response to exercise and making prescription or monitoring of exercise unreliable. Thus, these individuals may benefit from RPE regulated exercise that allows self-selected workloads that adequately stress the cardiorespiratory system. The primary finding of this study was that UT exercise can be safely performed by those with iSCI that satisfies the recommendations for aerobic activity level as prescribed by RPE.

Individuals with iSCI wishing to participate in UT exercise can most benefit from estimating their level of intensity to an RPE equivalent of 5 and 7 using a 1 to 10 scale. It should be noted that fitness and SCI level can affect self-selected treadmill speeds. However, sensory and motor function limitations among those with iSCI may alter RPE estimations depending upon lesion level and severity, thus future research should include a wider range of lesion level and severity. In conclusion, this study showed that those with iSCI are capable of increasing UT exercise workloads according to RPE that result in linear increases in heart rate and oxygen consumption.

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APPENDIX FOR STUDY I

APPENDIX A

Institutional Review Board Approval Letter

IRB

INSTITUTIONAL REVIEW BOARD
Office of Research Compliance,
010A Sam Ingram Building,
2269 Middle Tennessee Blvd
Murfreesboro, TN 37129

MIDDLE TENNESSEE STATE UNIVERSITY

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Monday, January 13, 2020

Principal Investigator	**Tyler William Langford** (Student)
Faculty Advisor	Jennifer Caputo & Sandra Stevens
Co-Investigators	Richard Farley, Dana Fuller and Vaughn Barry
Investigator Email(s)	*twl2q@mtmail.mtsu.edu; jcaputo@mtsu.edu; sandra.stevens@mtsu.edu*
Department	Health and Human Performance
Protocol Title	***Metabolic cost of underwater treadmill walking in individuals with and without incomplete spinal cord injury***
Protocol ID	**20-2086**

Dear Investigator(s),

The above identified research proposal has been reviewed by the MTSU Institutional Review Board (IRB) through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures*. A summary of the IRB action and other particulars in regard to this protocol application is tabulated below:

IRB Action	**APPROVED for ONE YEAR**		
Date of Expiration	**12/31/2020**	Date of Approval	1/13/20
Sample Size	30 (THIRTY)		

Participant Pool	Target Population 1: Primary Classification: **General Adults (18 or older)** Specific Classification: **Healthy individuals who meet the American College of Sports Medicine guidelines** Target Population 2: Primary Classification: **General Adults (18 or older)** Specific Classification: **Disabled individuals incomplete spinal cord injury with lesions at T7 or below**
Exceptions	Participant contact information is permitted to coordinate this research
Restrictions	**1. Mandatory SIGNED adult informed consent.** **2. Direct interaction only; NOT approved for online data collection.** **3. Not approved to collect identifiable information, such as, audio/video data, photographs, handwriting samples, financial information, personal address, driving records, social security number, and etc.** **4. Mandatory final report (refer last page).**
Approved Templates	MTSU templates: signature informed consent Non-MTSU template: Recruitment scriptl
Comments	NONE

Post-approval Actions

The investigator(s) indicated in this notification should read and abide by all of the post-approval conditions (https://www.mtsu.edu/irb/FAQ/PostApprovalResponsibilities.php) imposed with this approval. Any unanticipated harms to participants, adverse events or compliance breach must be reported to the Office of Compliance by calling 615-494-8918 within 48 hours of the incident. All amendments to this protocol, including adding/removing researchers, must be approved by the IRB before they can be implemented.

Continuing Review (**The PI has requested early termination**)

Although this protocol can be continued for up to THREE years, The PI has opted to end the study by **12/31/2020** **The PI must close-out this protocol by submitting a final report before** **12/31/2020** **to close-out may result in penalties including cancellation of tl** **protocol.** **collected using this**

Post-approval Protocol Amendments:

Only two procedural amendment requests will be entertained per year. *In addition, the researchers can request amendments during continuing review. This amendment restriction* *does not apply to minor changes such as language usage and addition/removal of research personnel. .*

Date	Amendment(s)	IRB Comments
NONE	NONE.	NONE

Other Post-approval Actions:

Date	IRB Action(s)	IRB Comments
NONE	NONE.	NONE

Mandatory Data Storage Requirement: All research-related records (signed consent forms, investigator training and etc.) must be retained by the PI or the faculty advisor (if the PI is a student) at the secure location mentioned in the protocol application. The data must be stored for at least three (3) years after the study is closed. TN State data retention requirement may apply. The PI must consult with MTSU Office of Data Management. Subsequently, the data may be destroyed in a manner that maintains confidentiality and anonymity of the research subjects.

The MTSU IRB reserves the right to modify/update the approval criteria or change/cancel the terms listed in this letter without prior notice. Be advised that IRB also reserves the right to inspect or audit your records if needed.

Sincerely,

Institutional Review Board
Middle Tennessee State University

Quick Links:

- Post-approval Responsibilities: http://www.mtsu.edu/irb/FAQ/PostApprovalResponsibilities.php
- Expedited Procedures: https://mtsu.edu/irb/ExpeditedProcedures.php

CHAPTER IV

ASSESSMENT OF A SELF-PACED PROTOCOL FOR TESTING MAXIMAL AEROBIC CAPACITY IN INDIVIDUALS WITH INCOMPLETE SPINAL CORD INJURY

Introduction

In the United States, there are an estimated 17,000 new spinal cord injury (SCI) cases each year (Jain et al., 2016). Dependent upon the level and the severity of injury, aerobic exercise capacity can be markedly reduced following an incomplete SCI (iSCI). Compared to ambulatory individuals, those with an iSCI tend to perform less daily physical activity, increasing their risk for further health complications (Buchholz, McGillivray, & Pencharz, 2003; Buchholz & Pencharz, 2004). Training and/or rehabilitation that increases the aerobic capacity of patients with iSCI is essential. In conjunction, there is a need to quantify changes in aerobic capacity which requires aerobic exercise testing (Eerden, Dekker, & Hettinga, 2018).

Maximal oxygen consumption (VO_{2Max}) is the best representation of an individual's aerobic capacity (Armstrong & Welsman, 2007). Assessment of VO_{2Max} during exercise testing has shown variable results dependent upon the mode of exercise and protocol adopted for testing (Eerden et al., 2018). The large increases in workload across stages in many protocols, such as with the incremental Bruce protocol, are often too fatiguing for those with gait impairment and limited aerobic capacity (Sisto & Evans, 2014). For individuals with an iSCI, a low initial metabolic cost with small to moderate progressive increments has been recommended (Eerden et al., 2018; Jamieson et al., 2008). One option is to design protocols based on the perceived exertion of individuals, allowing flexibility among varied participants. Mauger and Sculthorpe (2012) investigated a self-paced exercise protocol on a cycle ergometer among healthy adults during which each stage was anchored to an increasingly more difficult rating of perceived exertion (RPE) until maximal exertion or an RPE of 20. The participants produced a greater VO_{2Max} (40 ± 10 mL/kg/min Vs. 37 ± 8 mL/kg/min) and power output (273 ± 58 Watts Vs. 238 ± 55 Watts) compared to a traditional, graded exercise test (GXT). This may be a more feasible protocol for those with musculoskeletal dysfunction and limited exercise capacity, such as those with an iSCI.

An additional concern is that the loss of muscle mass following a spinal cord injury limits viable exercise modalities (Hopman, Verheijen, & Binkhorst, 1993; Jacobs & Nash, 2004; Silfhout et al., 2016; West, Mills, & Krassioukov, 2012; Zimmer, Nantwi, & Goshgarian, 2007). To maximize the achievable VO_{2peak} during testing, modalities requiring the greatest amount of muscle mass are recommended (Riebe et al., 2016). The limited unassisted ambulation ability associated with iSCI hinders the utility of using the common choice of a treadmill for maximal exercise testing. However, underwater treadmill (UT) exercise is a recent and sparsely tested modality that may be beneficial for those with iSCI. The buoyant force of water allows easier ambulation for individuals with an iSCI and less reliance on restrictive body harnesses or therapists (Stevens & Morgan, 2015). Currently, maximal oxygen consumption and HR has yet to be assessed during UT exercise among those with an iSCI. Therefore, the purpose of this study was to determine whether an RPE-based, maximal exertion protocol used in conjunction with an UT can elicit criterion-based maximal physiological variables among individuals with and without an iSCI. A second purpose of this study was to determine whether different maximal physiological values (VO_2, HR) would be achieved by those with and without iSCI. It was hypothesized that the RPE-based protocol would elicit maximal VO_2 and HR among participants with and without iSCI. It was further hypothesized that those without iSCI would achieve significantly greater VO_2 and HR values compared to those with iSCI.

Methodology

Participants

Healthy adults males with iSCI (*n* = 4; Age *M* = 49.8 $\pm$ 3.9 years) and without iSCI (*n* = 4; Age *M* = 50.0 $\pm$ 7.2 years) participated in this study. Participants were included in the study if they were 20 - 65 years old and, for those with iSCI, more than 1-year post-incident with a lesion at T7 and below (Grigorean et al., 2009; Hector, Biering-Sorensen, & Krassioukov, Biering-Sorensen, 2013). All participants with iSCI provided physician documentation of their iSCI, American Spinal Cord Injury Impairment Scale (AIS) rating and provided medical clearance to engage in laboratory testing. Those without iSCI were screened using the American College of Sports Medicine (ACSM) health screening algorithm (ACSM, 2018) for vigorous activity exercise. Table 1 includes descriptive data for all study participants. This research study was approved by the university Institutional Review Board (see Appendix A) and participants provided written informed consent prior to commencement of data collection.

Table 1

Descriptive Characteristics of Study Participants (N = 8)

	Group	
Variable	iSCI (*n* = 4)	Non-iSCI (*n* = 4)
Body mass (kg)	92.0 ± 14.0	86.8 ± 11.9
Height (cm)	180.1 ± 3.6	175.4 ± 14.2
Age (years)	49.8 ± 3.9	50.0 ± 7.2
Years since injury	9.4 ± 4.3	--

Note. Values are *M* ± *SD*. iSCI = Incomplete spinal cord injury.

Instrumentation

Anthropometric measurements

Body mass for those with a SCI was measured with participants in light clothing and without shoes, on a wheelchair scale (Seca 674, Hamburg, Germany). The wheelchair was weighed separately, and its mass subtracted to obtain the mass of the individual. Body mass for participants without SCI was measured in light clothing, without shoes, on the same scale, also to the tenth of a kilogram (Seca 674, Hamburg, Germany). Height was measured in an upright position without shoes using a standard stadiometer, unless participants were unable to achieve and maintain this position. If participants were unable to achieve an upright standing position, height was measured using a measuring tape without shoes in the supine position. Measurements were made from the top of the head to the bottom of the heel with the knees extended as much as possible. Segmental measurements were made, and summed, if full extension of the knees was not possible.

Rating of perceived exertion

The Borg OMNI RPE scale was used by participants to estimate their intensity of exercise (Borg, 1982). This is a 1-10 scale that is commonly used to subjectively assess levels of intensity during exercise (Borg, 1982).

Oxygen consumption

Oxygen consumption (VO_2) was measured via a portable Oxycon VO_2 system (Jager, Wurzburg, Germany). Gas calibration (environmental settings and gas-analyzer calibration) was performed before every testing session. This process required approximately 15 minutes for the system to warm-up and stabilize followed by ambient air and tank gas testing. Both high and low values were used for gas calibration (O_2 = 21%, CO_2 = 5%, and O_2 = 16%, CO_2 = 0.04%, respectively). Prior to each test, automatic volume calibration was performed following manufacturer instructions.

Procedures

Each participant reported to the lab on two occasions. During the first visit, participants without an iSCI completed informed consent papers and ACSM Algorithm Screening to assure medical clearance was not needed (ACSM, 2018). Participants with iSCI submitted medical clearance and AIS rating paperwork. Anthropometric measures were completed after paperwork was completed. Participants then performed a familiarization session with the testing equipment. The participants donned a HR monitor (Polar Electro Inc., Lake Success, NY) and were fitted with the mask for collecting expiratory gas (Hans Rudolph, Shawnee, Kansas). The HR monitor was securely strapped below the pectoral muscle, approximately at the xiphoid process. Heart rate was transmitted continuously to a watch outside of the UT. Each participant sat for 5 minutes to become accustomed to the equipment and practice breathing while wearing the mask.

Participants then entered the UT (HydroWorx, Middletown, PA) for familiarization. Individuals using wheelchairs were transferred from their wheelchair onto a sitting platform within the foyer of the UT. Once the foyer filled with water, all participants were able to float over to the treadmill belt. If needed, participants could place their arms on designated areas within the tank for support. The treadmill speed began at 0.5 miles per hour (mph). This speed was maintained for 3 minutes, at which point the treadmill speed was increased to 0.75 mph and maintained for another 3 minutes. Next, the participant was asked to self-select a speed representative of an RPE equivalent to 3 on the 0-10 scale. A dial on the outside of the tank was used to adjust the speed of the treadmill for 1 minute until the participant indicated the speed was appropriate. This speed was then maintained for 2 minutes. Immediately after, the participant was given 1 minute to self-select a treadmill speed for an RPE of 5, which was also maintained for 2 minutes. Subsequently, participants repeated this process to achieve an RPE of 7. Next, the treadmill was stopped so the participant could exit the treadmill and to end the first session.

Incremental exercise test protocol

Participants completed a speed-based, self-regulated incremental exercise test on the UT during their second visit. Participants were instructed to avoid strenuous exercise during the 48 hours prior to testing. Prior to the participant's arrival for all testing, the UT was filled and set to a temperature of 92° F. Upon arrival, participants donned the HR monitor and the mask for gas collection. Before entering the treadmill, participants remained seated for 3 minutes for the collection of resting data. Water height was modified to be at the height of each participant's xiphoid process.

The test consisted of rest, warm-up, incremental exercise, and active recovery phases. For the warm-up, the treadmill speed was adjusted to 0.5 mph for 3 minutes. After walking for 3 minutes, the speed was increased to 0.75 mph for another 3 minutes. The incremental exercise phase was a closed-loop protocol consisting of four stages, 3 minutes in duration, totaling 12 minutes. For each of the four stages, participants, respectively, self-selected a speed perceived to be at each of the following RPE levels: 3, 5, 7, and 10. The treadmill speed was hidden from participants during all testing. At the beginning of each stage, treadmill speed was adjusted during the first minute until the participant reached the appropriate RPE. During the final stage, participants were allowed to increase the treadmill speed freely until volitional exhaustion. The test ended when the participant reached volitional exhaustion, at which point the speed of the treadmill was lowered to a comfortable speed for an active recovery. During the active recovery, treadmill speed was gradually decreased based on the participant's preference until the participant was ready to exit the UT.

Measurements

A breath-by-breath system was used for continual monitoring of pulmonary gas exchange and ventilatory measurements (Oxycon), and VO_2 was reported as 30 second averages. During analysis, confirmation of VO_{2Max} attainment consisted of these criteria: breath-by-breath change in $VO_2 \leq 2.0$ mL/kg/min between the final VO_2 and the nearest data point during the last 60 seconds of exercise (plateau in VO_2; Astorino et al., 2000), ± 10 bpm of estimated max HR (HR_{Max}) using the equation (208-[0.7 x age]), due to its smaller range of error compared to previous calculations (Taylor, Buskirk & Henschell, 1995; Tanaka, Monahan, & Seals, 2001), and maximal respiratory exchange ratio (RER) ≥ 1.10 (Astorino et al., 2000). Two out of the 3 criteria needed to be met to indicate achievement of VO_{2Max}. If not, a VO_{2Peak} was indicated. The highest VO_2 and HR values achieved were used for analysis.

Statistical Analysis

Statistical analysis was completed using Statistical Package for the Social Sciences (SPSS) 26.0 (Chicago, IL, USA) software program. Statistical significance was predetermined at $p < 05$. Descriptive statistics and physiological values are reported as $M \pm SD$. An independent samples t-test was used to compare the length (minutes) until volitional exhaustion for those with and without iSCI. Separate independent samples t-tests were used to compare the highest achieved HR and VO_2 values for both iSCI and non-iSCI.

Results

Test Outcome and Duration

Individual peak physiological variables can be found in Table 2. All iSCI participants (*n* = 4) were considered to have achieved a peak VO_2. Only 1 participant without iSCI (*n* = 4) was considered to have achieved a VO_{2Max}. The mean test duration was not statistically different, *t*(6) = 0.59, p = .11, for those with iSCI (*M* = 13.8, *SD* = 4.9) and those without iSCI (*M* = 12.3, *SD* = 1.5).

Physiological Responses

Mean peak HR was similar, *t*(6) = 2.81, *p* = .06, among participants with iSCI (*M* = 121 bpm, *SD* = 30 bpm) compared to those without iSCI (*M* = 164 bpm, *SD* = 7 bpm). Mean peak VO_2 was significantly lower, *t*(6) = 3.81, *p* = .027, for those with iSCI (*M* = 13.88 mL/kg/min, *SD* = 10.57 mL/kg/min) compared to those without iSCI (*M* = 34.50 mL/kg/min, *SD* = 2.38 mL/kg/min). Mean peak RER was not significantly different, *t*(6) = 1.92, *p* = .12, between those with iSCI (*M* = .94, *SD* = .06) and those without iSCI (*M* = 1.06, *SD* = .12).

Table 2

Peak Physiological Data (N = 8)

Group	HR	VO_2	RER	AIS rating	Age (years)
iSCI	83	5.3	0.89	A	55
	124	10.7	0.95	C	50
	122	10.2	0.90	B	48
	156	29.3	1.01	D	46
Non-iSCI	157	34.1	1.14		60
	162	34.7	0.91		49
	165	31.7	1.17		48
	173	37.5	1.03		43

Note. HR = Heart rate in bpm; VO_2 = Oxygen consumption in mL/kg/min; RER = Respiratory exchange ratio; AIS = American Spinal Cord Injury Impairment Scale (AIS) rating; iSCI = Incomplete spinal cord injury.

Discussion

The purpose of this study was to determine whether an RPE-based, graded exercise test used in conjunction with an UT could elicit criterion-based maximal physiological variables among similarly aged individuals with and without an iSCI. The second purpose of this study was to determine whether there would be a difference in VO_2 and HR achieved by participants with and without iSCI. To our knowledge, this is the first study to utilize the UT as a modality for testing maximal cardiorespiratory fitness in those with an iSCI. Further, this is the first known study to implement an RPE-regulated protocol in conjunction with an UT. Both the UT and the use of RPE to regulate progressive increases in intensity were selected specifically to accommodate those with iSCI, who often have gait and exercise capacity limitations (Jacobs & Nash, 2004). The primary finding of this study was that an RPE-regulated protocol in an UT did not effectively elicit maximal cardiorespiratory responses from individuals either with or without iSCI. Secondly, the UT, RPE-regulated protocol elicited greater VO_2 responses among those without iSCI compared to those with iSCI. However, peak HR was similar between those with and without iSCI.

In this study, participants were asked to estimate a treadmill speed that would be associated with maximal exertion (RPE 10) following 9 minutes of progressive increases in submaximal exercise intensities, which were also self-regulated (RPE 3, 5, and 7). This design was unique due to the open-ended nature of the test, which continued until the participant requested to stop the test in order to accommodate those with iSCI. Traditionally, the stages of a maximal exertion test utilize predetermined workloads in an incremental protocol intended to elicit maximal cardiorespiratory responses within 8 to

10 minutes (Yoon, Kravitz, & Robergs, 2007). However, individuals with a limited exercise capacity can fatigue prematurely during graded exercise tests if the initial workload or the incremental increases in workload are too great.

Using the current protocol, each participant was able to vary his work rate for a given RPE, which may have prevented the use of excessive incremental workloads and premature fatigue for those with iSCI. Only one of these participants with iSCI (AIS D) was limited by the maximal speed (7 mph) of the treadmill. In contrast, while only one of the participants without iSCI achieved a criterion based VO_{2Max}, this participant did not reach the maximal treadmill speed. In fact, only one participant without iSCI reached the treadmill's maximal speed during the final stage. Previously, an RPE-regulated graded exercise test on a land-based treadmill has been reported to successfully elicit maximal VO_2 values among able-bodied individuals (Mauger, Metcalfe, Taylor, & Castle, 2013).

The reason(s) that most of the able-bodied participants in the current study did not achieve the maximal physiological criterion is uncertain. In contrast to Mauger et al., (2013), the current protocol was open-ended which allowed participants to continue exercise beyond 10 minutes. It is possible that these participants did not perceive an exercise end-point during the final stage (RPE 10) of the test. In other words, rather than self-selecting an increase in workload sufficient to achieve the maximal cardiorespiratory criterion, the participants of the current study gradually increased workload during the final minutes of the test. Therefore, the longer test duration could have resulted in lower extremity fatigue due to the resistive nature of the water and, ultimately, affected RPE. In fact, the able-bodied participants anecdotally commented after testing of lower extremity fatigue, while dyspnea was not maximal. However, this was not assessed in the current study and future researchers may consider assessing the RPE of the lower extremity simultaneously with a scale of dyspnea.

Mixed results have been reported for able-bodied individuals achieving peak or maximal cardiorespiratory responses during UT graded exercise tests (Schaal, Collins, & Ashley, 2012; Silvers, Rutledge, & Dolny, 2007). The current study, in contrast to the afore mentioned, did not include the use of jet propulsion to increase the workload during testing. Regardless, only one able-bodied participant self-selected the maximal speed provided by the treadmill, which would have warranted the use of jet propulsion. Further, the participants in the current study were much older and not required to be competitive runners. For the able-bodied population, cardiorespiratory responses to maximal UT exercise may be affected by protocol, age, fitness and water level, and the inclusion of jet propulsion. One limitation of the current study was a lack of comparison to a land-based treadmill, thus future research is warranted to determine the reliability of UT exercise testing.

In comparison to the able-bodied participants, one participant with iSCI (AIS D) self-selected the treadmill's maximal speed at the onset of the final stage, but also only achieved peak test values. This individual was the only participant with iSCI who did not require a wheelchair. Thus, the current protocol may not be practical to assess cardiopulmonary exercise capacity among those with and without iSCI using the UT. However, individuals with iSCI participating in UT training have been shown to achieve improvements in their cardiorespiratory responses to UT exercise (Stevens & Morgan, 2015). Thus, those participating in UT training can benefit from using an RPE-regulated protocol to assess training induced changes in peak VO_2. To the authors' knowledge, this is the first study to test aerobic fitness using the UT among those with iSCI.

Arm cranking exercise is a common modality for determining cardiorespiratory fitness in those with SCI (Jacobs & Nash, 2004). In comparison to upright exercise, arm cranking involves the use of smaller musculature and is associated with a lower venous return and cardiac output (Van Loan, McCluer, Loftin, & Boileau, 1987). In an UT, individuals with iSCI are provided with natural body weight support and a greater venous return from water (Stevens & Morgan, 2015). In the current study, those with iSCI may have been limited by lower extremity strength needed to achieve workloads high enough to elicit maximal physiological responses. Individuals with iSCI (AIS C and D) have been reported to achieve higher peak VO_2 values during incremental robotic-assisted treadmill exercise (RATE; 2.24 $\pm$ 0.51 L/min) versus arm crank ergometry (1.93 $\pm$ 0.34 L/min; Jack, Purcell, Allan, & Hunt, 2010). In the current study, mean peak VO_2 during UT exercise was 1.20 $\pm$ 0.72 L/min. When only including those with linear increases in VO_2, mean peak VO_2 increased to 1.45 $\pm$ 0.64 L/min. Further, the participant in this study with a less severe iSCI (AIS D) achieved a peak VO_2 (2.19 L/min) like that found during RATE. Thus, variability exists between the severity of iSCI and the highest achievable VO_2 during ambulatory exercise. In regards to UT exercise, those with a less severe iSCI (AIS D) may be more suitable for testing maximal oxygen consumption using this modality.

In the current study, mean peak HR was similar between those with and without iSCI. Similarly, those with and without SCI achieved similar maximal HR responses during arm cranking exercise (Jehl et al., 1991). The authors concluded that these individuals may have exhibited an exaggerated HR response due to central limitations such as a reduced venous return (Jehl et al., 1991). However, the majority of participants in the current study did not achieve their age-predicted maximal HR during testing (see Table 3). Thus, it is unclear whether HR responses of participants with iSCI in the current study were subject to central limitations. Although, the hydrostatic pressure of water is expected to increase the return of blood flow from the periphery and could attenuate any exaggerated HR response during exercise due to blood pooling. However, it is uncertain whether this may have occurred in the current study.

In conclusion, the current study has shown that the UT is a safe modality for graded exercise testing among those with and without iSCI. The use of an RPE-regulated protocol may not be effective for eliciting criterion-based maximal cardiorespiratory results with the UT setting. However, this study has shown that it is possible to assess peak cardiorespiratory measures using the UT. Further, it was found that an RPE-regulated protocol for a graded exercise test was well tolerated by those with iSCI. Being able to use the UT to test peak cardiorespiratory fitness among those with iSCI allows clinicians to track improvements in economy following UT training. Continued research on the use of this modality is encouraged with larger samples to further evaluate potential testing protocols among this population.

Table 3

Self-Selected Treadmill Speeds at each RPE (N = 8)

	Treadmill Speed (mph)		
Group	RPE 10	AIS rating	Age (years)
iSCI	3.85	A	55
	1.65	C	50
	1.50	B	48
	7.00	D	46
Non-iSCI	7.00		60
	6.15		49
	6.45		48
	5.55		43

Note. iSCI = Incomplete spinal cord injury; RPE = Rating of perceived exertion; AIS = American Spinal Cord Injury Impairment Scale (AIS) rating.

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APPENDIX FOR STUDY II

APPENDIX A

Institutional Review Board Approval Letter

IRB

INSTITUTIONAL REVIEW BOARD
Office of Research Compliance,
010A Sam Ingram Building,
2269 Middle Tennessee Blvd
Murfreesboro, TN 37129

IRBN001 - EXPEDITED PROTOCOL APPROVAL NOTICE

Monday, January 13, 2020

Principal Investigator	**Tyler William Langford** (Student)
Faculty Advisor	Jennifer Caputo & Sandra Stevens
Co-Investigators	Richard Farley, Dana Fuller and Vaughn Barry
Investigator Email(s)	*twl2q@mtmail.mtsu.edu; jcaputo@mtsu.edu; sandra.stevens@mtsu.edu*
Department	Health and Human Performance
Protocol Title	***Metabolic cost of underwater treadmill walking in individuals with and without incomplete spinal cord injury***
Protocol ID	**20-2086**

Dear Investigator(s),

The above identified research proposal has been reviewed by the MTSU Institutional Review Board (IRB) through the **EXPEDITED** mechanism under 45 CFR 46.110 and 21 CFR 56.110 within the category *(4) Collection of data through noninvasive procedures*. A summary of the IRB action and other particulars in regard to this protocol application is tabulated below:

IRB Action	**APPROVED for ONE YEAR**		
Date of Expiration	**12/31/2020**	Date of Approval	1/13/20
Sample Size	30 (THIRTY)		
Participant Pool	Target Population 1: Primary Classification: **General Adults (18 or older)** Specific Classification: **Healthy individuals who meet the American** **College of Sports Medicine** **guidelines** Target Population 2: Primary Classification: **General Adults (18 or older)** Specific Classification: **Disabled individuals incomplete spinal cord injury with lesions at T7 or below**		
Exceptions	Participant contact information is permitted to coordinate this research		
Restrictions	5. **Mandatory SIGNED adult informed consent.** 6. **Direct interaction only; NOT approved for online data collection.** 7. **Not approved to collect identifiable information, such as, audio/video data, photographs, handwriting samples, financial information, personal address, driving records, social security number, and etc.** 8. **Mandatory final report (refer last page).**		
Approved Templates	MTSU templates: signature informed consent Non-MTSU template: Recruitment scriptl		
Comments	NONE		

Post-approval Actions

The investigator(s) indicated in this notification should read and abide by all of the post-approval conditions (https://www.mtsu.edu/irb/FAQ/PostApprovalResponsibilities.php) imposed with this approval. Any unanticipated harms to participants, adverse events or compliance breach must be reported to the Office of Compliance by calling 615-494-8918 within 48 hours of the incident. All amendments to this protocol, including adding/removing researchers, must be approved by the IRB before they can be implemented.

Continuing Review **(The PI has requested early termination)**

Although this protocol can be continued for up to THREE years, The PI has opted to end the study by **12/31/2020** **The PI must close-out this protocol by submitting a final report before 12/31/2020** **Failure to close-out may result in penalties including cancellation of the data collected using this protocol.**

Post-approval Protocol Amendments:

Only two procedural amendment requests will be entertained per year. *In addition, the researchers can request amendments during continuing review. This amendment restriction does not apply to minor changes such as language usage and addition/removal of research personnel. .*

Date	Amendment(s)	IRB Comments
NONE	NONE.	NONE

Other Post-approval Actions:

Date	IRB Action(s)	IRB Comments
NONE	NONE.	NONE

Mandatory Data Storage Requirement: All research-related records (signed consent forms, investigator training and etc.) must be retained by the PI or the faculty advisor (if the PI is a student) at the secure location mentioned in the protocol application. The data must be stored for at least three (3) years after the study is closed. TN State data retention requirement may apply. The PI must consult with MTSU Office of Data Management. Subsequently, the data may be destroyed in a manner that maintains confidentiality and anonymity of the research subjects.

The MTSU IRB reserves the right to modify/update the approval criteria or change/cancel the terms listed in this letter without prior notice. Be advised that IRB also reserves the right to inspect or audit your records if needed.

Sincerely,

Institutional Review Board
Middle Tennessee State University

Quick Links:

- Post-approval Responsibilities: http://www.mtsu.edu/irb/FAQ/PostApprovalResponsibilities.php
- Expedited Procedures: https://mtsu.edu/irb/ExpeditedProcedures.php

CHAPTER V

OVERALL CONCLUSIONS

The UT is a safe alternative to a land-based treadmill and arm ergometry for both those with and without iSCI. Therefore, it is important to study the physiological responses to UT exercise. In the first study in this dissertation, the metabolic responses to submaximal UT exercise were explored among those with and without iSCI. In the second study, the use of an RPE-based a graded exercise test in the UT was explored.

In the first study, UT exercise was shown to elicit increases in VO_2 linear to increases in self-selected workload among those with and without iSCI. When walking at 0.50 mph and 0.75 mph, there were similar HR and VO_2 values between groups. These speeds are similar to those used during locomotor training for those with iSCI, who may be limited in cardiorespiratory capacity. In comparison to other methods of locomotor training, an UT limits complications with patient transfers, body support equipment, and therapist assistance. Therefore, those with iSCI may receive more benefit from participating in UT exercise compared to exercise on a land-based treadmill.

Participants were also asked to regulate the intensity of exercise by producing three different target RPE values. Using RPE, those with iSCI effectively self-selected a moderately intense exercise, however, the relationship between RPE and HR may be affected depending on the severity of injury. Regardless, prescribing exercise based on RPE for those with iSCI appears to be safe and appropriate to elicit a training response. Further, participants with iSCI were able to achieve submaximal VO_2 values similar to those previously reported for other modalities of exercise. Thus, using RPE to prescribe exercise may be more efficient for those with iSCI because there is not a need for equipment for monitoring HR or preliminary testing to determine training workload. However, more research is warranted because the level and severity of iSCI can affect an individual's perceived effort or work capacity. Future researchers should look to compare VO_2 and HR between UT exercise and other modalities.

The aim of the second study was to determine whether an RPE-based, graded exercise test used in conjunction with the UT could be used to measure VO_{2Max} among similarly aged individuals with and without an iSCI. A second purpose was to determine whether there would be a difference in VO_2 and HR achieved by participants with and without iSCI, respectively. The RPE protocol did not effectively elicit maximal cardiorespiratory responses from individuals either with or without iSCI. In fact, only one participant achieved criterion-based maximal physiological values. However, this could have been due to an excessive test duration causing premature muscle fatigue. Future research should limit the duration of the test so that participants may envision a final sprint to the end, so to speak. Still, using incremental stages based on RPE during a graded exercise test on a treadmill may be an effective method for testing the peak VO_2 in those with varying levels of iSCI, which limits speed more than fitness level. By using this method, clinicians are able to avoid causing premature fatigue by prescribing excessive initial workloads or excessive incremental increases in workload.

There were greater peak VO_2 responses among those without iSCI compared to those with iSCI. However, there was variability in the VO_2 responses among participants with iSCI, which indicated that those with a less severe iSCI (ASIA D) may be more suitable for testing maximal VO_2 using the UT. This study has shown that it is possible to assess peak cardiorespiratory measures using the UT. Thus, clinicians can use this protocol in the UT to test peak cardiorespiratory fitness among those with iSCI and track improvements in economy or fitness level following UT training. Continued research on the use of this modality is encouraged with larger samples to further evaluate potential testing protocols among this population.

In conclusion, the results of this dissertation provide information to assist clinicians and researchers in exercise testing individuals with iSCI. Those with iSCI are capable of achieving moderate levels of activity intensity when exercising in the UT that may translate into cardiorespiratory benefits. However, an RPE-regulated graded exercise test using the UT may not effectively elicit maximal VO_2 and HR among those with and without iSCI.

DISSERTATION REFERENCES

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