A WALK TO A BETTER TOMORROW: IMPROVING FUNCTIONAL MOBILITY IN ADULTS WITH INCOMPLETE SPINAL CORD INJURY

by

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ABSTRACT

The objective of this dissertation was to increase the body of knowledge related to functional mobility and physical activity in adults with incomplete spinal cord injury (SCI). By identifying key determinants which underlie the recovery of walking in persons with SCI, a foundation can be laid to develop and implement activity-based interventions which can enhance community ambulation and physical health in this physically-challenged population. To explore this topic, two studies were performed. The primary aim of Study 1 was to explore interrelationships among lower-extremity strength, preferred walking speed, and daily step activity in 21 adults (17 males, 4 females; age = 39 ± 12 years; 3 ± 2 years post-injury) with incomplete SCI and to quantify the proportion of explained variance in daily step activity accounted for by leg strength and preferred walking speed. Analysis of data collected in Study 1 revealed the presence of statistically significant associations of moderate to strong magnitude ($r = .74 - .87$) among lower-limb strength, normal walking speed, and daily step counts. In addition, lower-extremity strength and preferred walking speed accounted for 83% of the variance in daily step activity. Results obtained from Study 1 provided the basis for conducting Study 2, which documented the effects of an 8-week underwater treadmill training (UTT) program on lower-extremity strength, balance, and five indices of functional walking performance in 11 adults (7 males, 4 females, age = 48 ± 14 years; 5 ± 8 years post-injury) with incomplete SCI. Findings from this second investigation revealed that UTT produced significant improvements of moderate to strong magnitude in leg strength, balance, preferred and rapid walking speeds, 6-minute walk distance, and daily step activity. Viewed collectively, results from both Studies 1 and 2 provide support for contemporary theories which suggest that the adult central nervous system has the capacity to repair and reorganize itself following SCI and that this regenerative process is facilitated by engaging in a systematic program of regular walking that features graduated increases in intensity and duration.

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LIST OF ABREVIATIONS

SCI = Spinal cord injury

BWSTT = Body weight supported treadmill training

EMG = Electromyography

DGO = Driven gait orthotics

UTT = Underwater treadmill training

SAM = Step activity monitor

SPSS = Statistical Package for the Social Sciences

LEMS = Lower-extremity motor scale

CHD = Coronary heart disease

DEXA = Dual energy x-ray absorptiometry

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PROJECT INTRODUCTION

Current evidence indicates that there are approximately 12,000 new spinal cord injuries (SCI) in the United States each year (National Spinal Cord Injury Statistics Center, 2009). Approximately 259,000 individuals in the United States are currently living with SCI, the majority of which are males who are less than 40 years of age (National Spinal Cord Injury Statistics Center). Because of advances in the emergency treatment of acute SCI and the long-term management of this condition, the longevity of persons with SCI has increased over the past decade (Krause & Broderick, 2005). This has led to the development of new technologies to improve functional performance and decrease secondary health consequences related to sedentary living among individuals with SCI (Lavis, Scelza, & Bockenek, 2007). In addition to the increase in the survival rate of persons with SCI, the immediate administration of methylprednisolone sodium succinate, which tends to reduce inflammatory responses, has lessened the extent of neural degeneration and subsequent impairment (Barbeau, Ladouceur, Norman, Pepin, & Leroux, 1999). Hence, more persons with SCI have the potential for restoration of walking.

Independent community ambulation has been reported as a high priority for individuals experiencing motor loss following SCI (Dobbins et al., 2007). While conventional rehabilitation programs are designed to facilitate independence in performing functional tasks such as walking, loss of muscle strength and motor coordination limit the capacity of individuals with SCI to participate in traditional overground ambulation training regimens (Gittler, McKinley, Stiens, Groah, & Kirshblum, 2002). Over the past two decades, body-weight-supported treadmill training (BWSTT) has been proposed as an activity-based intervention to improve walking ability following incomplete SCI (Wirz et al., 2005). BWSTT consists of unloading a portion of a person's body weight above a motorized treadmill using a counter-weight harnessing system and providing manual assistance, as needed, to advance the lower extremities in a normal stepping pattern. Use of BWSTT has been shown to enhance lower-extremity muscle function as revealed by electromyographic (EMG) assessment. In a recent study documenting EMG activity, participants receiving BWSTT training demonstrated activation patterns in the rectus and biceps femoris, tibialis anterior, and gastrocnemius muscles that were more similar to those observed in a control group of non-injured individuals compared to a group of SCI patients receiving traditional ambulation training (Lunenburger, Bolliger, Czell, Muller, & Dietz, 2006). In addition, improvement in functional walking ability, as measured by the Walking Index for Spinal Cord Injury (WISCI-II), the 10-meter walk test (10MWT), the 6-minute walk test (6MWT), and the Timed Up & Go test (TUG), has been shown to occur in several studies which have featured BWSTT (Behrman & Harkema, 2000; Dietz & Harkema, 2004; Wirz et al., 2005).

While BWSTT has led to increased muscle strength and locomotor ability in persons with SCI, concerns have been raised regarding both the number of therapists needed to implement this training modality and the physical demands placed upon therapists involved in BWSTT. Protocols incorporating BWSTT sometimes require up to three therapists to simulate the natural motion of the lower extremity and provide pelvic stabilization (Wirz et al., 2005). In addition, the quality of sensory input provided by the therapists can influence the effectiveness of the training gains made by persons with SCI who undergo BWSTT (Galvez, Budovitch, Harkema, & Reinkensmyer, 2007). To address these concerns, driven gait orthotic (DGO) devices have been developed to mimic the kinematics of ambulation. The DGO is an exoskeletal apparatus attached to the pelvis and the lower extremities that moves the legs through symmetric, coordinated motions replicating the physiological patterns of walking. In combination with body-weight support, the DGO provides essential sensory cues which stimulate neuronal circuits in the uninjured portions of the spine and generate intrinsic stepping activity (Ivanenko, Poppele, & Lacquaniti, 2009). The use of this type of training in the rehabilitation setting could potentially improve locomotor function by increasing the duration of training sessions and reducing labor- and cost-intensive demands placed on therapists (Wirz et al., 2005).

While DGO training appears promising, problems with this approach have been noted. For instance, in a study documenting the metabolic costs associated with BWSTT and DGO, it was reported that the energy demands of DGO walking were less than those measured during BWSTT. It has been hypothesized that the reduced energy expenditure of DGO walking may be related to the external guidance (especially during the swing phase of gait) and pelvic stability provided by the device (Israel, Campbell, Kahn, & Hornby, 2006). In contrast, if the ultimate goal of gait training is to improve walking capability in real-world settings, a realistic metabolic challenge must be presented to participants. Additional criticisms of DGO use include the presence of abnormal patterns of muscle activation and intensity and inappropriate sensory cues attributed to a fixed ankle position, resulting in a greater stretch placed on the knee flexors during imposed knee extension (Galvez et al., 2007). Taken together, these limitations suggest that DGO training is a more passive form of orthopedic rehabilitation that may hinder the overall recovery of ambulation in persons with SCI (Israel et al., 2006). While less costly than BWSTT, DGO interventions are expensive, and the purchase and training costs associated with this form of therapy, as well as limited reimbursement from third-party payers, may restrict the availability of this therapy for persons with SCI.

Given the drawbacks and limitations associated with therapies such as BWSTT and DGO training, other options to improve functional mobility in persons with SCI should be explored. One such alternative is underwater treadmill training (UTT). Observations of individuals walking in an aquatic environment suggest that water buoyancy provides a more comfortable and normal unloading for deconditioned persons than that produced by a harnessing system featuring point-specific unloading (Giaquinto, Ciotola, & Marqutti, 2007). Water walking also allows for normal deviation in gait to occur, enabling participants to express the individual characteristics of their own gait. Without the pelvic stability provided by a harnessing system, participants who walk in an underwater setting are able to experience greater excursions of weight shift and take advantage of longer reaction times to correct inappropriate alterations in balance. These features of underwater treadmill training may lead to improved core stability and balance, both of which are necessary to perform overground walking. In addition, walking in an aquatic environment maximizes afferent feedback in all directions, which may heighten the ability of cutaneous sensory receptors to influence step cycle activity (McCrea, 2001).

As a training medium, use of the underwater treadmill enables clinicians and researchers to easily and efficiently manipulate and reproduce gait speed, water depth, and water temperature, all of which can affect metabolic responses to exercise (Byrne, Craig, & Wilmore, 1996). Other advantages of underwater treadmill exercise include the similarity of muscle activity and gait patterns used in land walking, minimization of postural distortions that often characterize forward walking in water, increased leg strength gained by overcoming water resistance and turbulence, enhanced range of motion, and decreased pain (Bryne et al., 1996; Napoletan, 1994). While the impact of UTT has not been documented in the SCI population, anecdotal information suggests that this form of water therapy may address a number of limitations encountered with alternative unloading systems, while capitalizing on the benefits of this approach to increase functional ambulation (Groopman, 2003).

Regardless of the training approach employed, a major difficulty encountered when designing intervention protocols to improve gait function is that relatively little is known regarding key variables, such as leg strength and gait speed, which underlie walking potential in persons with SCI (Dobbins et al., 2007). Assuming that leg strength and walking speed can be modified through UTT, a clear understanding of the extent to which these variables contribute to home and community ambulation would be helpful in designing training protocols. Furthermore, the impact of well-controlled water-based walking therapy on functional ambulation in persons who have experienced spinal cord damage has not been documented. Against this backdrop, the dual purposes of this dissertation were to explore interrelationships among walking speed, lower extremity muscle strength, and daily step activity in adults with spinal cord injury and to quantify the effects of underwater treadmill training on locomotor function, leg strength, and balance in this population.

CHAPTER II

LOWER-EXTREMITY STRENGTH AND WALKING SPEED AS PREDICTORS OF DAILY STEP ACTIVITY IN ADULTS WITH INCOMPLETE SPINAL CORD INJURIES

Introduction

Injury to the human spinal cord typically interrupts the transmission of efferent and afferent neural signals, both of which are necessary for complex motor behaviors, such as ambulation, to occur. The ensuing loss of walking ability leads to a reduction in daily physical activity, which results in atrophy of motor neurons and a further decrease in physical activity. Using an animal model, Gazula, Roberts, Luzzio, Jawad, and Kalb (2004) reported marked atrophy in the spinal motor neurons of rats after complete transaction of the spinal cord. However, similar atrophy was not observed in animals with transacted spinal cords who engaged in exercise of the impaired limbs.

Reduced levels of physical activity among adults with spinal cord injury (SCI) contributes to the increased risk of coronary heart disease observed in this population (Lavis, Scelza, & Bockenek, 2007; Myers, Lee, & Kiratli, 2007). In addition, autonomic dysfunction, which is often present in persons with SCI, can result in heart rate variability, arrhythmia, abnormalities in blood pressure, and a blunted cardiovascular response that can limit the capacity to perform physical activity (Myers et al., 2007). For individuals with long-term SCI, mortality from cardiovascular disease exceeds that caused by renal and pulmonary conditions, both of which have been identified as primary causes of death in previous decades (Myers et al.). Risk factors commonly associated with cardiovascular disease and physical inactivity, such as obesity, lipid disorders, metabolic syndrome, and diabetes, also tend to be more prevalent in individuals with SCI compared to persons displaying normal ambulatory profiles (Lavis et al., 2007). Additionally, daily energy expenditure is significantly lower in persons with SCI due to the loss of motor function and decreased opportunities to engage in physical activity (Myers et al.). Collectively, these findings suggest that rehabilitative efforts geared towards improving walking performance in individuals with SCI may potentially yield a number of positive health outcomes.

In designing intervention strategies to mitigate the decline in physical function observed in persons with SCI, it is critical to identify key factors which promote effective ambulation in community settings. Two potential variables of interest include lower-extremity strength and walking speed, both of which decline following SCI. If walking bouts require greater strength than can be generated, or if a walking task cannot be completed in a reasonable amount of time, more efficient forms of mobility (e.g., wheelchairs, motorized scooters) can be employed to compensate for limitations in walking status. While these compensatory strategies allow individuals with SCI to become more functionally mobile, they also paradoxically contribute to a reduction in walking behavior in this population (Bottos & Gericke, 2003).

When assessing gait status following SCI, specific limitations in lower-extremity strength have been noted. Ditunno and Scivoletto (2009) have suggested that interventions to improve gait function in this clinical population should address weakness in the hip extensors and flexors, knee flexors and extensors, and ankle dorsiflexors. They also stated that poor hip extension during the stance phase of gait, which is usually linked to weakness in the gluteal muscles, contributes to pelvic drop, which further limits gait performance in persons with SCI. Likewise, in a study identifying early predictors of walking recovery following SCI, preservation of lower-extremity strength was shown to be the best predictor of functional ambulation (Dobkin et al., 2007).

Declines in walking speed have also been tied to impaired ambulatory status following SCI (Dobkin et al., 2007). In a review focusing on walking recovery after injury to the spinal cord, slow walking speeds were found to contribute to longer total step duration, a shorter stride length, and a lengthening of stance and swing times (Barbeau, Ladouceur, Norman, Pepin, & Leroux, 1999). These alterations in temporal aspects of gait appear to be directly related to slower walking velocities rather than to other gait features which emerge as a result of neural damage (Barbeau et al., 1999). Although speculative, the increased demand placed on weak extensor muscles during the lengthened stance phase may limit effective ambulation in persons with SCI. Conversely, if stance duration is shortened by increasing walking speed, extended walking efforts might be realized.

In summary, ambulation has been associated with independent living and fewer secondary health consequences in persons with SCI (Lavis et al., 2007). The impact of strength and speed deficits on the walking ability of persons with SCI has primarily been documented using outcome measures such as the Functional Independence Measure-Locomotor sub-section, the Walking Index for Spinal Cord Injury-II, walking speed for 50 feet, or the distance covered in a 6-min walk test (Ditunno & Scivoletto, 2009). While all of these assessments provide valid clinical measures of walking capability, their ecological validity is somewhat limited because they do not reflect walking performance in real-life settings. Consequently, a primary focus of this study was to explore relationships among lower-extremity strength, preferred walking speed, and step activity in home and community settings in adults with incomplete SCI. In addition, a complementary purpose of this investigation was to quantify the separate and combined influences of leg strength and locomotor velocity on daily step activity in this physically-challenged population.

Methods

Participants. Adults (males, *n* = 17; females, *n* = 4) with incomplete SCI, recruited through contacts with local clinicians and SCI community groups, volunteered to participate in this study. Participants ranged in age from 21 years to 61 years, were classified as either American Spinal Cord Injury Association level C or D, and displayed injury levels from C_4 to S_1. Interviews were conducted to determine project eligibility. All participants were at least 1-year post-accident, were capable of ambulating at least 10 feet with or without an assistive device, and did not exhibit complex co-morbidity. This project was approved by the university Institutional Review Board and written informed consent was obtained prior to data collection.

Measurement of lower-extremity strength. Leg strength was measured using a handheld dynamometer (Commander PowerTrack II, J-Tech Medical, Salt Lake City, UT). The use of hand-held dynamometry to quantify muscle strength has been shown to be highly reliable (interclass correlation coefficients > .91) when assessing persons with neurological disabilities (Riddle, Finucaine, Rothstien, & Walker, 1989). In addition, hand-held dynamometers have been reported to demonstrate good validity in the lower force ranges in persons post-polio, with validity and reliability increasing when stabilization techniques are implemented and experienced examiners perform the strength measurements (Nollet & Beelen, 1999).

Prior to determining leg strength, participants were securely positioned, with proximal stabilization provided to minimize muscle substitution and ensure appropriate force application by the muscle groups tested. Maximal isometric lower-extremity strength was assessed during flexion, extension, and abduction of the hip, flexion and extension of the knee, and ankle dorsiflexion and plantar flexion. These muscle groups were selected based on their demonstrated contribution to effective ambulation in persons with SCI (Kim, Eng, & Whittaker, 2004). Muscle groups were tested in the same order in an attempt minimize the physical exertion associated with multiple position changes. Each joint was placed in as close to a 90 degree angle as possible, with the dynamometer placed at the distal end and perpendicular to the segment being tested. Exceptions to this procedure were hip abduction, dorsiflexion, and plantar flexion, which were measured from a neutral position. Joint angles were determined using a standard goniometer.

A minimum of three trials were completed for each muscle group in both legs. Verbal directions and physical prompts were provided to facilitate the appropriate direction of force application. During each trial, participants were instructed to press as hard as possible against the dynamometer, which was held in place by the tester ("make test"). When maximal effort appeared to be met (~ 3 to 5 seconds), participants were instructed to relax. The highest achieved strength values measured in the seven muscle groups tested in each leg were summed to yield an overall lower-extremity strength score. The method of expressing muscle strength as a sum, has been implemented in previous testing in the SCI population (Dobkin et al., 2006; Geisler, Dorsey, & Coleman, 1991).

Body mass was measured using a wheelchair scale calibrated with standard weights to enable lower limb strength to be expressed relative to body mass.

Measurement of preferred walking speed. Walking speed was measured using a Brower Timing System as participants walked over a level indoor surface. Participants were instructed to walk at a comfortable pace for 3.048 meters (10 feet). Preferred walking speed was calculated from the time (to 1/100 of a second) required to transverse a 2-meter distance located in the middle of the walking course. Participants completed at least three walking trials with adequate rest breaks between each trial. Mean preferred walking speed was obtained by averaging walking speeds across multiple trials. Additional walking trials were completed if difficulty, such as the loss of balance or failure of an assistive device to work properly, was experienced in previous walking attempts. The first three trials performed at a pace described by the participant as normal were used to calculate preferred walking speed.

Measurement of daily step activity. Home and community walking activity was documented using the Step Activity Monitor (SAM) (OrthoCare, Oklahoma City, OK). The SAM is a micro-processor-driven accelerometer that measures the quantity and relative intensity of walking activity. The SAM has been validated for individuals with incomplete SCI. Bowden and Behrmen (2007), for instance, reported that the SAM was 97% accurate compared to hand-tallied step counts during 10-m and 6-min walk tests when worn by individuals with SCI. Additional validation of the SAM was conducted in a published SCI case study reporting 98% accuracy between manual counts and those recorded by the SAM (Behrman et al., 2005) in a person with an incomplete $C_{5\text{-}6}$ SCI.

During the testing session, each participant was fitted with a SAM to assess daily step activity at home and in the community. Prior to wearing the SAM, initial calibration adjustments were made for the expected sensitivity, cadence, threshold, and motion characteristics of each participant. Participants were then observed during overground walking to ensure that all step activity was captured. If step counts were missed or if non-step activity was registered, further adjustments to the SAM were made until all valid step activity was registered. Once programming of the SAM was completed, it was attached (using a Velcro strap) to the right leg. If participants wore an orthotic device on the right ankle, they were instructed to wear the SAM on the left ankle to increase the likelihood of recording all valid step activity (Bowden & Behrman, 2007).

The step activity monitors were worn during waking hours (except when showering or bathing) for seven consecutive days, beginning the day following laboratory testing. Step counts were recorded in 1-minute epochs and the SAM was automatically reset to zero at the end of each day. Following the 7-day monitoring period, the SAM was returned to the primary investigator to allow stored activity data to be downloaded and processed. If step activity data were missing or incomplete, participants were asked to wear the SAM for the number of days necessary (either during the following weekend or the following week) to complete seven full days (five week days and two weekend days) of data acquisition. Because step count data from the SAM reflect activity from only one leg, the step activity of both legs can be calculated by doubling the step activity of the monitored leg.

Data Analysis

Data were analyzed using SPSS Version 16.0. Descriptive statistics are presented as means ± standard deviations. Pearson product-moment correlation analysis was performed to quantify relationships among lower-extremity muscle strength, preferred walking speed, and daily step activity. Multiple regression analysis was employed to quantify the predictive value of lower-extremity strength and preferred walking speed in estimating daily step activity. Trend analyses were conducted to determine the pattern of distribution for leg strength and preferred walking speed relative to daily step activity. A significance level of .05 was used for all analyses.

Results

Descriptive statistics for leg strength, preferred walking speed, and daily step activity of study participants are presented in Table 1. As shown in Table 2, statistically significant correlations of moderate to high magnitude were observed among leg strength, preferred walking speed, and home and community-based daily step activity. Results from multiple regression analysis presented in Table 3 also indicated that leg strength and preferred walking speed collectively accounted for 83% of the variation in daily step counts.

Table 1

Leg Strength, Preferred Walking Speed, and Daily Step Activity of Study Participants

Variable	*M*	*SD*	Range
Leg strength (N·kg^{-1})	10.30	3.62	4.63 – 15.84
Preferred walking speed (m s^{-1})	0.43	0.21	0 – .77
Daily step activity (right leg only)	1167	770	10 – 2149

Table 2

Relationships Among Leg Strength, Preferred Walking Speed, and Daily Step Activity

	Leg strength (N·kg^{-1})	Preferred walking speed (m s^{-1})	Daily step activity (right leg only)
Leg strength (N·kg^{-1})	-	.74*	.83*
Preferred walking speed (m s^{-1})		-	.87*
Daily step activity (right leg only)			-

Note. *p < .05 (2-tailed)

Table 3

Regression Analysis Summary for Variables Predicting Daily Step Activity

Variable	*B*	*SE B*	*ß*
Leg strength ($N \cdot kg^{-1}$)	386.63	136.07	.41
Preferred walking speed ($m \cdot s^{-1}$)	936.04	237.35	.57

Note. Variable contribution to daily step activity: leg strength; $R^2 = .69^*$; preferred walking speed; $R^2 = .76^*$; R^2 from both leg strength and preferred walking speed = .83*. $^*p < .05$.

Trend analyses were conducted to illustrate the pattern of the relationships between lower-extremity strength and daily step activity (Figure 1) and preferred walking speed and daily step activity (Figure 2). The relationship between lower-extremity strength and daily step activity was best represented with a linear model, indicating that each increment of increase in strength was associated with a proportionate rise in daily steps. In contrast, a growth model was shown to best express the association between preferred walking speed and daily step count, such that greater increases in daily step activity occurred at faster walking velocities than at slower walking velocities.

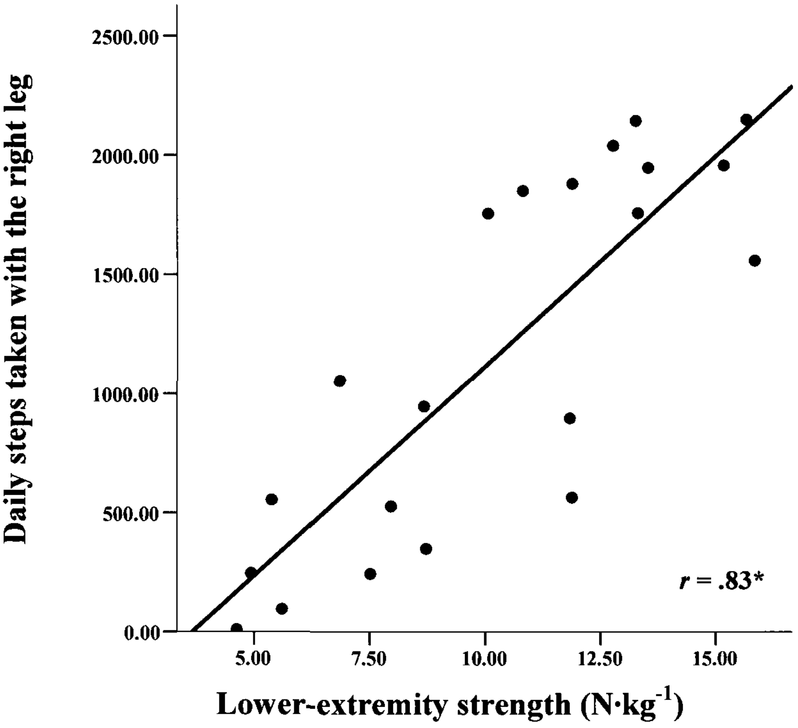

Figure 1. Trend analysis of the relationship between lower-extremity strength and daily step activity; *$p < .05$.

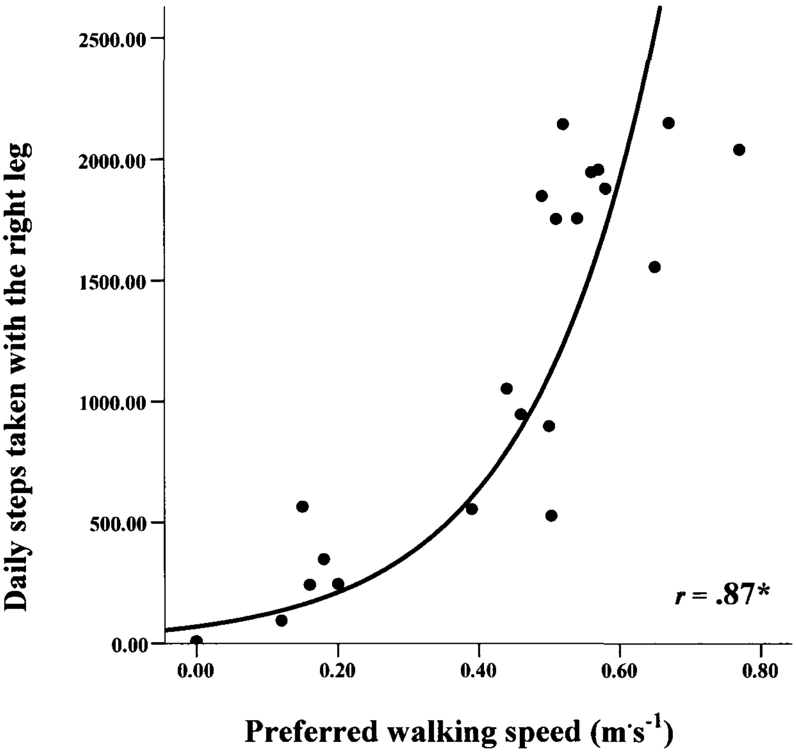

Figure 2. Trend analysis of the relationship between preferred walking speed and daily step activity; $*p < .05$.

Discussion

A primary aim of this investigation was to quantify relationships among lower-extremity strength, preferred walking speed, and daily step activity in adults with incomplete spinal cord injury. A secondary focus of this study was to assess the individual and collective influences of leg strength and locomotor velocity on daily step activity in adults with SCI. From a clinical standpoint, quantifying the contributions of ambulatory speed and lower limb strength to daily step activity in home and community environments is an essential first step towards developing effective activity-based therapies to improve locomotor function in this physically-challenged population.

Lower-extremity strength. Typically, strength assessment in persons with SCI is conducted using the lower extremity motor score (LEMS), which is a 0 to 5 rating scale based on the ability of muscles to resist gravity and external resistance. In this scale-based assessment, scores for individual muscle groups are summed to provide an overall strength score (Ditunno & Scivoletto, 2009). While the LEMS has been used to provide a general classification of muscle strength levels in the SCI population, subtleties in force production or modest changes in strength resulting from training or therapy, while clinically meaningful, may evade detection. An alternative to using the LEMS scale is hand-held dynamometry. This method of strength assessment has been employed in studies featuring neurologically-impaired populations (Nollet & Beelen, 1999; Wiley & Damiano, 1998) and has been shown to be valid at lower strength ranges (Nollet & Beelen) and highly reliable when testing is done using a “make test,” wherein the examiner holds the dynamometer in a stationary position while the participant exerts a maximum push against the dynamometer. In the current study, strength measures obtained from specific muscle groups in each leg were summed to derive a total relative lower extremity strength score. The method of summing muscle strength has been used in a variety of studies examining strength and neurological improvement in persons with SCI (Ditunno & Scivoletto, 2009; Dobkin et al., 2006; Geisler et al., 1991). However, because previous research in this area has employed scale-based measures of muscle strength in the SCI population (Ditunno & Scivoletto; Dobkin et al., 2006; Geisler et al.), it is not possible to compare our findings with those of other investigators. However, as shown in Table 1, marked variability was present in the residual leg strength of our participants, such that the overall strength score of the strongest participant was 342%

higher than the summed strength score of the weakest participant. Although speculative, this disparity in total leg strength may be related to interindividual differences in both the extent of neural sparing as well as intrinsic and extrinsic factors associated with recovery from spinal cord injury. Regardless of the individual manifestations of impairment, a reduction in leg strength typically occurs following SCI and the spontaneous recovery of leg strength has been identified as a primary predictor of ambulatory status (Kim et al., 2004).

Walking speed. Published evidence suggests that a walking speed of 1.2 m s^{-1} (Lapointe, Lajoie, Serresse, & Barbeau, 2001) to 1.31 m s^{-1} (van Hedel, Tomatis, & Muller, 2006) is required for independent community ambulation. The mean walking speed for our sample was 0.43 $\pm$ 0.21 m s^{-1}, a value similar to walking velocities of 0.36 m s^{-1} (Wirz et al., 2005) and 0.31 m s^{-1} (Winchester et al., 2009) recorded in other studies of male and female adults with SCI classified as AIS C and D. Taken together, these slower walking speeds fall below the suggested velocity required for independent community ambulation, thus setting the stage for an increased reliance on assistive mobility aids to facilitate locomotion.

It has been suggested that the reduction in walking speed seen in persons with SCI can be attributed to a reduction in gait cycle frequency caused by diminished neural processing speed. While stride length contributes to gait velocity, reductions in stride frequency appear to be the primary factor limiting locomotor velocity in persons with SCI (Pepin, Ladouceur, & Barbeau, 2003). These authors also noted that persons with SCI can accommodate increases in gait speed by adjusting stride length, but once maximum stride length has been achieved, no further increases in velocity are attainable

(Pepin et al.). Given this kinematic limitation, gait training following SCI should include activities which facilitate rapid reciprocal patterns of motion, such as assisted ambulation training that promotes a more rapid cyclical gait pattern (Pepin et al.)

Daily step activity. Current evidence suggests that for healthy adults, 6000 to 7,000 steps per day is reflective of usual daily activity (excluding sport and exercise participation) and values lower than this range are considered sedentary (Tudor-Locke, Bassett, 2004). Saraf et al. (2010) reported an average of 4310 (±2921) steps per day for persons with SCI who are community walkers and 1006 (± 1082) steps per day for persons with SCI who are not community walkers. These data highlight the extensive variability of daily step behavior in the SCI population, as well as the disparity between daily steps recorded in a population of ambulatory individuals and adults with SCI. Our sample of primarily non-community walkers with SCI displayed a mean step count of 1167 (±770) steps per day, a value similar in both overall magnitude and variability to that reported by Saraf and colleagues (2010). The limited step activity displayed by our participants is well below the threshold for sedentary persons identified by Tudor-Locke and Bassett (2004) and clearly points toward the need for enhanced physical activity in this population.

Correlational and multiple regression analysis. Statistically significant relationships of moderate to high magnitude ($r = .74$ to $.87$) were observed among lower-extremity strength, walking speed, and daily step activity in our sample of adults with SCI. These findings align with previous research demonstrating strong correlations between leg strength and walking speed $r = .62, p = .01$ (Dobkins et al., 2007) and leg strength and daily step activity, $r = .73, p < .01$ (Saraf et al. 2010) in persons who have experienced spinal cord injury. From a functional standpoint, the slower walking speed characteristic of persons with SCI results in an extended stance phase, which lengthens the time during which force must be generated by weaker propulsive muscles. The subsequent increase in muscle fatigue can lead to an even greater reduction in walking velocity, thus increasing the time required to traverse a given distance. Given this scenario, individuals with SCI may decide to forego a planned outing in the community, employ assistive technology to facilitate ambulation, or remain sedentary, all of which would reduce possible walking opportunities in home- and community-based settings.

In view of the preceding discussion, it appears reasonable to suggest that walking speed and leg strength are fundamental features associated with walking success in persons with SCI. In support of this assertion, multiple regression analysis revealed that the combined influence of leg strength and walking speed accounted for a vast majority (83%) of the variation in daily step activity in our participants. Given the association between daily physical activity and improved health in persons with SCI (Myers, et al., 2007), these findings suggest that rehabilitative efforts to enhance functional mobility in this group should focus on improving both lower-extremity strength and walking velocity.

While leg strength and walking speed were significant and substantial contributors to daily step activity, a different pattern of distribution for each variable relative to walking activity was observed. Specifically, trend analysis revealed that a linear model best depicted the relationship between leg strength and daily step activity (Figure 1), whereas the association between walking speed and daily step count was most accurately portrayed using a growth model (Figure 2). Visual inspection of Figure 2 lends credence to the notion that a critical speed (~ 0.42 $m \cdot s^{-1}$) may exist, above which daily step activity rises in a curvilinear fashion. This finding suggests that a primary aim of clinical interventions designed to promote ambulation in home and community environments among persons with SCI should be to reach and eventually exceed this speed threshold value. Interestingly, the estimated velocity threshold observed in the current study is identical to values reported for persons with myelomeningocele and stroke (0.42 $m\,s^{-1}$) (Barbeau et al., 1999) and is at the lower range of speed threshold values (0.40 to 0.80 $m \cdot s^{-1}$) needed to attain full community ambulation (Schmid et al., 2007).

In conclusion, results from the present study indicate that statistically significant relationships of moderate to strong magnitude exist among lower-extremity strength, walking speed, and daily step activity in male and female adults with incomplete SCI. In addition, a substantial majority of the explained variance in daily step activity in persons with SCI can be predicted from knowledge of leg strength and preferred walking speed. Based on these findings, future research- and clinically-based efforts to enhance home and community mobility in this physically-challenged population should be directed towards increasing lower limb strength and walking speed.

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APPENDICES

Appendix A

MTSU Institutional Review Board Approval: Study 1

6/3/2008
Protocol Number: 08-330
Title: Walking Speed, Leg Strength…
Investigators: Stevens, Sandy; Morgan, Don
stevens@tnstate.edu; dmorgan@mtsu.edu

Dear Investigators:

The MTSU Institutional Review Board, or a representative of the IRB, has reviewed the research proposal identified above. With the inclusion of your responses to questions on 6/3/2008 (attached), the MTSU IRB or its representative has determined that the study poses minimal risk to participants and qualifies for an expedited review under 45 CFR 46.110 and 21 CFR 56.110.

Approval is granted for one (1) year from the date of this letter for **20** participants.

According to MTSU Policy, a researcher is defined as anyone who works with data or has contact with participants. Anyone meeting this definition needs to be listed on the protocol and needs to provide a certificate of training to the Office of Compliance. **If you add researchers to an approved project, please forward an updated list of researchers and their certificates of training to the Office of Compliance (c/o Tara Prairie, Box 134) before they begin to work on the project.** Any change to the protocol must be submitted to the IRB before implementing this change.

Please note that any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918.

You will need to submit an end-of-project report to the Office of Compliance upon completion of your research. Complete research means that you have finished collecting and analyzing data. **Should you not finish your research within the one (1) year period, you must submit a Progress Report and request a continuation prior to the expiration date.** Please allow time for review and requested revisions.

Also, all research materials must be retained by the PI or faculty advisor (if the PI is a student) for at least three (3) years after study completion. Should you have any questions or need additional information, please do not hesitate to contact me

Sincerely,

Sincerely,
Robert K. Kalwinsky, Ph D.
rkalwins@mtsu.edu

Appendix B

Informed Consent Document for Research: Study 1

Middle Tennessee State University Institutional Review Board
Informed Consent Document for Research

Principal Investigator: Sandy Stevens **Date: 4/15/08**
Study Title: Walking speed, leg strength, and functional ambulation in adults with incomplete spinal cord injuries

Institution: Middle Tennessee State University

This informed consent document applies to adults

Name of participant ______________________________ Age ________

The following information is provided to inform you about the research project and your participation in it. Please read this form carefully and feel free to ask any questions you may have about this study and the information given below You will be given an opportunity to ask questions, and your questions will be answered. Also, you will be given a copy of this consent form.

Your participation in this research study is voluntary You are also free to withdraw from this study at any time In the event new information becomes available that may affect the risks or benefits associated with this research study or your willingness to participate in it, you will be notified so that you can make an informed decision whether or not to continue your participation in this study

1. **Purpose of the study:**
   You are being asked to participate in a research study because of your experience with spinal cord injury The purpose of this study is to determine if walking speed and leg strength can be used as predictors of functional ambulation in adults with spinal cord injuries

2. **Description of procedures to be followed and approximate duration of the study:**
   As a participant in this study, you will be asked to walk approximately 15 feet, during which, your walking speed will be measured After the walk is completed, the strength of your lower extremities will be determined You will also be asked to wear a step activity monitor which will count the number of steps you take over a seven week period In addition to these tasks, you will participate in a personal interview with the primary investigator so that demographic and health status information can be gathered Following the interview and assessments, the care and use of the step activity monitor will be explained The entire testing session will last approximately two hours

3. **Expected costs:**
   There are no costs associated with this study

4. **Description of the discomforts, inconveniences, and/or risks that can be reasonably expected as a result of participation in this study:**
   There are no known risks involved in the collection of this data Walking speed will be assessed under normal indoor walking conditions over level ground The muscle testing will feature a noninvasive procedure requiring you to exert your best effort The step activity monitor is a lightweight apparatus attached to the right ankle by an adjustable Velcro strap

5. **Unforeseeable risks:**
   There are no unforeseeable risks

6. **Compensation in case of study-related injury:**
   No compensation will be provided

7. **Anticipated benefits from this study:**
   a) The potential benefits to science and humankind that may result from this study are related to mobility outcomes for adults with spinal cord injuries Persons with spinal cord injuries are often restricted to a sedentary lifestyle because of difficulty with walking Limited ambulation in this population may be related to

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Date 13/08

and walking speed, both of which have been observed in this population If interventions can be identified to improve these skills, improvements in independent walking may follow

8. **Alternative treatments available:**
   No alternative treatment is available

9. **Compensation for participation:**
   No monetary compensation will be provided

10. **Circumstances under which the Principal Investigator may withdraw you from study participation:**
    You may be withdrawn from the study if you are not able to complete any of the tests associated with this investigation

11. **What happens if you choose to withdraw from study participation:**
    Participation in this project is completely voluntary Participation may be discontinued at any time without risk of prejudice or penalty

12 **Contact Information.** If you should have any questions about this research study or possibly injury, please feel free to contact Sandy Stevens at (615)963-7490 or my Faculty Advisor, Don Morgan at (615)898-5549 For additional information about giving consent or your rights as a participant in this study, please feel free to contact the Office of Compliance at (615) 494-8918

13. **Confidentiality.** All efforts, within reason, will be made to keep the personal information in your research record private but total privacy cannot be promised Your information may be shared with the MTSU University Institutional Review Board or if you or someone else is in danger or if we are required to do so by law

STATEMENT BY PERSON AGREEING TO PARTICIPATE IN THIS STUDY

I have read this informed consent document and the material contained in it has been explained to me verbally. All my questions have been answered, and I freely and voluntarily choose to participate.

Date ____________________ Signature of patient/volunteer ____________________

Consent obtained by

Date ____________________ Signature ____________________

Printed Name and Title ____________________

Adapted from Vanderbilt University

CHAPTER III

IMPACT OF UNDERWATER TREADMILL TRAINING ON LOWER-EXTREMITY STRENGTH, BALANCE, AND FUNCTIONAL MOBILITY IN ADULTS WITH INCOMPLETE SPINAL CORD INJURY

Introduction

The restoration of walking has been cited as a high priority for persons experiencing loss of physical function as a result of a spinal cord injury (SCI) (Fouad & Pearson, 2004). A growing knowledge base relative to the neuronal control of ambulation has led to the emergence of promising treatments to improve ambulatory function and promote the recovery of walking in the SCI population.

One strategy which has gained popularity in the rehabilitation of individuals with SCI is the use of body weight-supported treadmill training (BWSTT). A number of studies have shown that treadmill training stimulates patterned afferent activity in persons with incomplete SCI, leading to improved walking performance (Dietz, 2009; Deitz & Colombo, 1994; Edgerton & Roy, 2009; Fouad & Pearson, 2004; Wriz, et al., 2005). It is thought that this type of afferent input excites neuronal networks in the spine which produce stepping behaviors (Harkema, 2001). The BWSTT regimen involves supporting a portion of a person's body weight through the use of a counter-balanced harnessing system, while manual assistance is supplied to stabilize the pelvis and move the legs. As training progresses, body weight support is gradually reduced and less assistance is provided to simulate natural phases of gait. Once training has ceased, the positive effects of BWSTT can persist for an extended period of time. Moreover, if self-sustained walking is achieved, gains in ambulatory status can be retained by integrating walking into normal daily activities (Wernig, Nanassy, & Muller, 2000). For BWSTT to be effective, the application and replication of normal patterns of muscle activation are required, as this patterning is considered necessary to generate appropriate sensory input to stimulate adaptive changes in the neuronal networks of the spine (Harkema). Put more simply, normal afferent input generated by BWSTT is required to facilitate normal efferent output.

While BWSTT has been shown to improve walking in persons with neurological impairments (Fauad & Pearson, 2004; Wirz et al., 2005), a number of methodological issues exist which limit both the practicality of this rehabilitative approach and the attainment of optimal locomotor function. The repetitive facilitation of appropriate gait patterns is labor-intensive, requiring up to three trainers per person, and physically demanding for therapists to administer (Wirz et al.). In fact, the fatigue experienced by clinicians can supersede that observed in participants engaged in BWSTT and lead to a reduction in the duration of training sessions (Galvez, Budovitch, Harkema, & Reinkensmeyer, 2007). The skill of the trainer has also been cited as a potential limitation in BWSTT. Related to this point, Galvez et al. (2007) documented the manual assistance provided during BWSTT in persons with SCI and reported that the force application and direction and angle of the motions being facilitated varied among therapists. In addition, more skilled therapists elicited greater improvements in walking compared to less- or untrained staff members (Galvez). Because of the need to reproduce normal patterns of motion in persons undergoing BWSTT, any inconsistency in achieving this goal may diminish the potential effects of this intervention. In addition, the BWSTT harnessing system unloads the participant with a groin strap which can be uncomfortable and is sometimes contraindicated due to adverse cardiovascular and orthostatic responses (Krassioukov & Harkema, 2006), diminished sensory function, and a greater risk of pressure sores.

An alternative to BWSTT is the use of computer-driven gait orthotics (DGO), which provide robotic assistance to retrain walking behavior in participants with SCI (Wirz et al., 2005). DGO therapy allows for more consistent movements of the legs, while reducing the physical demands placed on therapists and the number of staff needed to supervise training sessions. Studies assessing the effectiveness of DGO training have reported improvements in stepping activity and overground walking ability in individuals with incomplete SCI (Wirz et al.). While DGO training has been shown to yield clinical and functional benefits, drawbacks associated with this rehabilitative approach have been noted. Because fatigue and poor endurance limit independent mobility in persons with SCI, the lowered metabolic demand of walking resulting from the passive guidance provided by the robotic aid during DGO training (Israel, Campbell, Kahn, & Hornby, 2006) may interfere with long-term recovery by decreasing the activation of muscle responses associated with independent walking, thus muting the aerobic training effect (Israel et al., 2006). Another drawback of DGO training is the generation of abnormal patterns of muscle recruitment and force production (Israel et al.) resulting from inappropriate sensory cuing due to a fixed ankle position. This atypical profile of muscle recruitment and force output can lead to an increased stretch placed on the knee flexors during imposed knee extension. While DGO is less labor-intensive than BWSTT, the substantial financial costs of DGO therapy, which include the purchase of specialized equipment as well as staff training, restrict the general availability of this intervention. Consequently, DGO training may be cost-prohibitive and beyond the reach of many persons with SCI.

While acknowledging the benefits of BWSTT and DGO therapy, limitations associated with each of these gait retraining techniques have provided an impetus to consider other options to improve walking performance in persons with SCI. An activity-based therapy that has received little clinical attention, but holds much promise, is underwater treadmill training. The use of a treadmill submerged in a self-contained tank allows for the precise control of walking speed, water depth, and water temperature, a trio of features which can impact training response and performance. In an aquatic environment, the level of body weight support supplied by the buoyant effects of water creates a more comfortable and realistic unloading of body mass than that provided by a harnessing system featuring point-specific unloading. In a harnessed-based system, the body is suspended but the full weight of the legs remains unchanged, whereas unloading in the water provides buoyancy to the legs and allows forward movement to occur with less force production required. Other advantages of water walking include generation of muscle activity and gait patterns similar to those seen in overground walking, minimization of postural distortions, greater weight-bearing support for deconditioned individuals, increased leg strength caused by overcoming water resistance and turbulence, and decreased spasticity (Byrne, Craig, & Wilmore, 1996; Giaquinto, Ciotola, Marqutti, 2007; Napoletan, 1994). Walking in a water environment also permits normal deviations in gait to be expressed, which allows participants to explore the unique characteristics of their walking style instead of having movement patterns artificially imposed by external assistance. Without the pelvic stability provided by a harnessing system, participants can experience greater excursions of weight shift, in conjunction with increased reaction time, to make small ongoing adjustments in balance. Consequently, dynamic stability, a critical variable in the acquisition of walking, may be enhanced by underwater treadmill training. Another potential benefit of exercising in an aquatic medium is an increase in activity tolerance caused by a reduction in pain due to the hydrostatic pressure of the water. By stimulating sensory transmission along faster Aα fibers, pain signals are interrupted. This theory of pain modulation, first presented 45 years ago by Melzak and Wall, has continued to provide a foundation for describing the interactions between local and distant facilitory and inhibitory systems integrated in the dorsal horn of the spinal cord (Dickenson, 2002).

From a neuromuscular perspective, stepping activity is promoted through the stimulation of central pattern generators. In theory, these reflexive steps are a subcortical response, arising from complex neural networks located in the spinal cord. This type of stepping behavior is automatic and may provide a foundation for volitional motor activity (Maegele, Muller, Wernig, Edgerton, & Harkema, 2002). If the movement of an overground treadmill belt facilitates reflexive stepping, afferent feedback from proprioceptive and cutaneous receptors in the legs may be amplified when treadmill walking occurs in an environment, such as water, which maximizes sensory input (McCrea, 2001).

As a final consideration, walking on a treadmill submerged in water may blunt the cardiovascular response to exercise typically observed following SCI. When autonomic nerve pathways are interrupted, as they are in SCI, active muscles may not receive adequate blood supply to sustain physical activity, especially when exercise is performed in an upright position (Krassioukov & Harkema, 2006). Consequently, venous return may be limited. In contrast, the hydrostatic pressure of the water promotes the return of blood to the heart, which enhances cardiac preload stroke volume and partially compensates for limited activity-related increases in heart rate.

In summary, while the use of body weight-supported treadmill training and computer-driven gait orthotics has led to improvements in walking ability following SCI, the potential of underwater treadmill training to enhance gait function in persons with spinal cord injury remains largely unexplored. Using water as a medium for body weight unloading is an innovative therapeutic approach which may enable physically-challenged individuals to benefit from partial weight support during ambulation, while simultaneously addressing a number of training-related issues related to harnessing, balance, pain, cardiovascular response, and the control of key exercise parameters. Against this backdrop, the purpose of this study was to document the effects of underwater treadmill training on lower-extremity strength, balance, and functional mobility in adults with incomplete SCI.

Methods

Participants. Adults with incomplete SCI (males, *n* = 7; females, *n* = 5) volunteered to participate in this investigation. Participants were recruited through flyers, local newspaper stories describing the study, and contacts with local clinicians and SCI community groups. Study enrollment criteria included being 21 years of age or older, the absence of complex co-morbidity, the ability to walk at least 10 meters with or without an assistive device, and being more than 1-year post accident. All volunteers were required to submit physician documentation of the SCI and provide medical clearance prior to testing and underwater treadmill training. Eleven of the 12 participants completed the program, as one participant withdrew from the study because of difficulty in securing reliable transportation to the testing site. Table 1 provides descriptive information for study participants. This study was approved by the university Institutional Review Board and all participants provided informed written consent prior to data collection.

Table 1.

Descriptive Characteristics of Study Participants

Sex	Age in years	Level of lesion	AIS	Years post-injury	WISCI-II	Primary mode of locomotion
M	56	T5	C	3	9	Wheelchair
M	62	C4	D	2.5	16	Ambulation
M	62	L2	C	6	16	Wheelchair
F	51	C3	C	3	6	Ambulation
M	43	T8	C	2	9	Wheelchair
M	28	L2	C	28	18	Wheelchair
M	23	C6	C	1.5	16	Wheelchair
F	64	C4	C	1	13	Ambulation
M	50	C2	C	1	11	Wheelchair
F	40	T6	D	3	9	Wheelchair
F	46	L2	C	2	13	Wheelchair

Note. M = male; F = female; ASI = American Spinal Injury Association Impairment Scale; WISCI-II = Walking Index for Spinal Cord Injury

Pre-training assessments. Each participant completed a pre-training test battery over a 3-hour period on a single day. Participants were transported from their cars using a golf cart or power wheelchair to limit the amount of walking activity prior to testing. The following sections describe the measurement of each primary outcome variable.

Leg strength. The JTech Commander PowerTrack II Muscle Dynamometer was used to assess lower-limb strength. Before strength data were obtained, participants were securely positioned in a chair or on a mat table, with proximal stabilization provided to minimize muscle substitution and ensure appropriate force application by the muscle groups tested. Maximal isometric leg strength during hip flexion, extension, and abduction, knee flexion and extension, and ankle dorsiflexion and plantar flexion was measured in both legs based on methodology and findings reported by Kim, Eng, and Whittaker (2004). In their study, statistically significant correlations were observed between the aforementioned lower-extremity muscle groups and ambulatory capacity, walking speed, and the 6-minute walk test in adults with SCI.

Prior to each strength measurement, the involved joint was positioned in midrange, as verified by a standard goniometer, to enable participants to achieve the greatest possible force production. Verbal directions, physical prompts, and an opportunity to practice each measurement at a submaximal force level were provided for each muscle group. The dynamometer was placed at the distal end and perpendicular to the segment being tested. A minimum of three trials were completed for each muscle group in both legs. Each participant was instructed to press as hard as possible against the dynamometer, which was held in place by the primary investigator. Verbal encouragement was provided during the testing process. When maximal effort appeared to be generated (~ 3 to 5 seconds), participants were instructed to relax. The highest achieved strength value for identical muscle groups in each leg were summed to provide a combined strength score for a given muscle group. The combined strength scores for the seven muscle groups that were evaluated were then added to derive a total lower-extremity muscle strength score. This summative approach to quantifying muscle strength has been validated in previous studies of strength and neurological improvement in the SCI population (Ditunno & Scivoletto, 2009; Dobkin et al., 2007; Geisler, Dorsey, & Coleman, 1991). To express muscle strength (in Newtons) relative to body size, a wheelchair scale calibrated with standard weights was used to determine the body mass of each participant.

Balance. Balance was measured using the Berg Balance Scale (BBS). The BBS, which has been featured in SCI intervention research (Ditunno & Scivoletto, 2009) and is sensitive to change, assesses balance during static and dynamic activities performed while seated and standing. This balance evaluation required participants to complete 14 tasks, ranging from sitting with feet on the floor with no back support to standing on one leg. Participants' performances on these tasks were combined to provide a numeric balance score ranging from 0 to 56.

Walking capacity. The Walking Index for Spinal Cord Injury (WISCI-II) was used to evaluate walking capacity in persons with SCI (Ditunno et al., 2000; Ditunno & Ditunno, 2001; Kim, Burns, Ditunno, & Marino, 2007). In this test, a walking score is generated based on the equipment needed and level of assistance required to complete a 10-meter walk. Participants were observed while walking 10 meters indoors over level ground. Each person was encouraged to walk as independently as possible, but allowed to use an assistive device, if needed, to successfully complete the test. The WISCI-II score was assigned based on the level of assistance used to complete the walk. Scores on the WISCI-II can range from 0 (signifying an inability to walk, even with maximum assistance) to 20 (indicating the ability to walk 10 meters without assistance or the use of a mobility device).

Walking speed. Walking speed was measured using the 10-meter walk test (10MWT). In this test, participants walked in a straight line for 14 meters at a normal, comfortable pace in an indoor gymnasium. Using two photoelectric cells, walking time was recorded during the central 10 meters of the course to account for potential acceleration and deceleration effects. Participants completed the test using assistive devices typically employed while walking in their natural environment. Each participant completed three walking trials and was allowed to rest as long as necessary between trials. From knowledge of distance and time, walking speed was calculated. The mean preferred walking speed for each participant was obtained by averaging speeds calculated for each walking trial. Following determination of preferred walking speed, participants who were able to walk at velocities exceeding their typical pace completed another set of three walking trials over the same course at the fastest pace they could safely sustain. Similar to procedures used to calculate mean preferred walking speed, the mean rapid walking speed for each participant was calculated by averaging speeds for the three fastest-pace trials.

In addition to calculating mean preferred walking speed, biweekly assessments of freely-chosen walking speed were completed during the 8-week training period. The purpose of acquiring these supplemental measures of preferred walking speed was to more fully document the nature of training-related changes in this ambulatory variable.

Walking endurance. The 6-minute walk test (6MWT) was administered to estimate the aerobic endurance of our sample. In this test, participants were asked to walk for six minutes around an oval course in a gymnasium with a wooden floor. Before testing commenced, each subject was instructed to cover as much distance as possible in the time allotted and allowed to select the method of assistive device use during the walking trial. Participants were followed with a wheelchair and given an opportunity to rest during the test, if needed. Total walking distance was recorded to the nearest foot with a calibrated measuring wheel and converted to meters traveled.

Daily step activity. Walking activity at home and in community settings was monitored using an Orthocare Step Activity Monitor (SAM). Calibration of the SAM featured initial adjustments for the expected sensitivity, cadence, threshold, and motion characteristics of each participant. Once the SAM was programmed for each participant, the monitor was attached, via a Velcro strap, to the less-involved leg. Participants were then observed during overground walking to ensure that all step activity was captured. If step counts were missed, or if non-step activity was registered, sensitivity, cadence, threshold, and motion values were readjusted until all valid step activity was registered. Prior to leaving the laboratory, participants were instructed in the care of and wearing schedule for the SAM.

Step activity monitoring began the day after calibration and participant fitting of the SAM. Step activity data were collected in 1-minute epochs during waking hours, for seven consecutive days, except during showering or bathing. The activity monitors were returned following the 7-day assessment period for downloading and processing of stored activity data. If step data were missing or incomplete, participants were asked to wear the monitor for the number of days necessary to complete seven full days of data acquisition. While specific days were not required for subsequent assessment, participants were asked to wear the monitor on weekend days (if weekend days were missed) or on weekdays (if weekday data were missing). If a participant inadvertently wore the monitor for more than 7 days, step activity data from the first 7 days of monitoring were analyzed. Because step count data from the SAM reflect activity from only one leg, the step activity of both legs can be obtained by doubling the step activity of the monitored leg.

Accommodation to underwater treadmill walking. Following the pre-training test battery, participants completed a treadmill accommodation session which involved walking in an aquatic environment. This practice session was also used to establish initial training parameters.

Prior to the start of the accommodation session, the weight-unloading system (LiteGait BiSym Suspension System, Model PBS 1637, Mobility Research) was calibrated. Load cells embedded within the suspension apparatus were calibrated incrementally from 0 kg (body harness and no weight) to 10 kg using 2-kg increments. The calibration process then continued from 10 kg to 55 kg in 5- to 25 kg- increments. Throughout this process, the load cells on the right and left sides of the LiteGait system were calibrated to share the load equally. Once the calibration process was completed, the self-contained, 270-gallon underwater treadmill tank (Hydro Track® Underwater Treadmill System) was filled almost completely with water.

Upon arriving at the testing site, each participant was fitted with a body harness. The harness was worn loosely around the mid-section of the body with no groin strap.

While the harness did not provide body weight support, it did serve to catch participants if they stumbled or slipped while walking on the treadmill. Participants entered the tank (either by floating or by taking a small step) from an adjacent foyer and were observed standing with no support from the harness. Participants were allowed to hold onto the handrails inside the tank while water height was adjusted to a level at which adequate buoyancy was achieved. Absolute levels of water height (i.e., absolute levels of body weight support) were established for each participant based on the minimum water height necessary to achieve and maintain an upright position with knees and hips in a maximally extended position during bilateral stance and with no support from the harness or upper extremities.

Once an appropriate water height was established, each participant walked for 1-minute at a speed that was either 50% slower than their preferred overground walking speed or 0.20 $m \cdot s^{-1}$, (the slowest speed setting on the treadmill), whichever was faster. If the water height allowed for an appropriate balance between support and loading during the 1-minute bout, it was recorded and used throughout the 8-week training program. The treadmill was then stopped and the participant was raised completely off of the bottom of the tank using a hydraulic suspension system. While the participant's body was supported by the harness, the water level in the tank was adjusted to bring the water to the preestablished location on the body. Body mass was then recorded from the load cell reading. The difference in body mass on land and body mass in the water was divided by the participant's land body mass and the quotient was multiplied by 100 to determine the percentage of body mass that was unloaded. The mean percentage of land body mass unloaded in this study was 38.3% (range = 29.8% to 47.2%).

After water height level was individually established for each participant, three 5-minute walks on the underwater treadmill were completed. Before starting these walks, participants were fitted with a Polar heart rate monitor. Heart rates were monitored continuously during exercise to evaluate cardiovascular response. As an extra safety measure, participants were asked to identify their rating of perceived exertion (RPE) at the conclusion of each walk. Verbal anchors for the Borg CR10 scale (Borg, 1998) are listed in Table 2.

Table 2

Descriptors for Borg CR10 Rating of Perceived Exertion

Numerical Rating	Descriptors
10 9	So tired, I can't go anymore
8 7	Really tired
6 5	Tired
4 3	A little tired
2 1	Not tired at all

At the beginning of the first 5-minute exercise trial, treadmill walking speed was initially set as described earlier (either 50% of each participant's preferred walking speed or 0.20 m s^{-1}, whichever was faster). Treadmill speed was gradually adjusted during the first minutes of exercise until an increase in heart rate was observed from standing heart rate, an RPE of at least 3 was reported, no adverse responses were observed (e.g. dizziness, changes in muscle tone, shortness of breath, pain), and appropriate levels of hip and knee extension were maintained. This final speed setting was used during the remaining accommodation trials and also served as the initial training speed during the first week of training. Rest periods of at least 5-minutes were personalized based on recovery rate and expressed preference of the participants, maximal rest periods of 10 minutes between walks was noted in this sample. While resting, participants were provided with a choice of standing or sitting in a floatation chair.

Despite their limited capacity to sustain overground ambulation, all participants were able to successfully complete three 5-minute underwater treadmill walks. Consequently, the duration of exercise trials in Week 1 of the underwater treadmill training program was set at 5-minutes to build upon this initial level of walking success and to avoid initially overtaxing or exceeding the aerobic capabilities of our participants (Lapointe et al., 2001). Our decision to have participants complete short intermittent bouts of walking instead of one extended walking session is also supported by data indicating that shorter activity bouts can yield fitness gains similar to those produced by a single exercise session and are often tolerated better by deconditioned individuals (Dunn, Marcus, Kampert, Garci, Kohl, & Blair, 1999; Haskell et al., 2007).

Water temperature for the treadmill accommodation session was initially set at 90°F. Participants were observed during the three walking bouts to assess the effect of water temperature on muscle tone and were asked to rate their response to the water temperature based on mobility (1 – "I am having difficulty moving my legs at this water temperature" to 5 – "I am not having any difficulty moving my legs at this water temperature") and comfort (1 – "I am uncomfortable at this water temperature" to 5 – "I am very comfortable at this water temperature"). If necessary, water temperature was adjusted until a rating of three or higher was registered for both questions. This final water temperature was used throughout the underwater treadmill training program unless a change was requested by the participant or adverse reactions (e.g., excessive sweating, abnormal rise in heart rate or RPE) were noted by the trainer.

Underwater treadmill training. Following the treadmill accommodation session, each participant completed 24 training sessions in approximately 8-weeks. Participants trained three times per week for 8-weeks. This training schedule was chosen based on evidence suggesting that 8-weeks of BWSTT is sufficient to produce measurable improvements in 10MWT, 6MWT, the Timed Up & Go test, lower-extremity motor scores, and spasticity in persons with SCI (Wirz et al., 2005). Each training session included three walks of equal duration with ample rest periods between walking bouts. In Session 1, participants completed three 5-minute walking bouts at the personalized water height, walking speed, and water temperature established during the treadmill accommodation session. In addition, heart rate was monitored using a Polar heart rate monitor for all training sessions and written recordings of serial heart rate values were obtained during the last 15 seconds of the final 2- minutes of each exercise bout. Immediately following the conclusion of each 5-minute walk, participants were shown a color-coded chart and asked to verbally report their RPE value.

During the study, scheduled increases in walking speed and duration were imposed in a systematic and gradual manner. The general outline of incremental adjustments in training parameters is shown in Table 3.

Table 3

Overview of Weekly Increments in Walking Speed and Duration

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
Speed	TA speed	10% increase	No change	10% increase	No change	10% increase	No change	10% increase
Duration	5-minute walks	No change	6-minute walks	No change	7-minute walks	No change	8-minute walks	No change

Note. TA speed = Treadmill accommodation speed

As depicted in this table, one aim of the training program was to increase walking speed twice a month, which resulted in four speed increases over the course of the 2-month training program. While the general outline for speed changes found in Table 3 served as an overall guide, biweekly increases in walking speed were personalized, depending on heart rate and RPE responses recorded during the previous week of training. It was expected that heart rates would decline as training continued at a given walking speed. If this expectation was met, walking speed was increased by 10% on the first day of the ensuing week of training. However, if the scheduled increase in walking speed resulted in heart rates exceeding 75% of the participant's age-adjusted maximal heart rate, or if RPE was greater than 5 (tired), treadmill walking speed was adjusted downward until these parameters were met. Fortunately, all but one of the participants were able to tolerate 10% biweekly increases in walking speed throughout the course of the study. For the single participant who exceeded the heart rate and RPE criteria identified earlier, walking speed was adjusted to maintain heart rate below 75% of age-adjusted maximal heart rate and to achieve an RPE value of five or lower. For this participant, biweekly speed increases varied between 5% and 10%.

As noted in Table 3, walking duration was increased in 1-minute increments during training sessions in Weeks 3 and 4, 5 and 6, and 7 and 8. These 1-minute increases were applied to each walking bout, resulting in an overall increase in duration of three minutes per training session. Hence, at the beginning of training (Weeks 1 and 2), participants completed three 5-minute walks and accumulated 15 minutes of total walking. However, in Weeks 7 and 8, all participants were able to perform three 8-minute walks for a total of 24 minutes of walking, resulting in a 60% increase in walking duration over the course of the study.

Post-training assessments. Following underwater treadmill training, participants completed post-training assessments identical to those conducted during the pre-training phase of the study. Similar to the approach used during pre-testing, post-training assessments were completed in a single 3-hour block within one week of the last training day.

Data analysis. Data were analyzed using SPSS version 17.0. Repeated-measures analysis of variance (ANOVA) was conducted to evaluate pre- to post-training changes in leg strength, balance, walking capacity, preferred and fastest walking speeds, walking endurance, and daily step activity. Additional ANOVA tests were conducted to compare strength gains in the stronger and weaker leg and strength gains across individual muscle groups. Trend analysis was also used to explore the pattern of biweekly changes in preferred walking speed during the 8-week training program. A significance level of .05 was established for all statistical analyses.

Results

Descriptive statistics for pre-and post-training measurements of leg strength, balance, and functional mobility are shown in Table 4. As shown in Table 5, findings from the repeated-measures ANOVA demonstrated that participants exhibited significant relative improvements in leg strength (57%), balance, (39%) preferred walking speed (34%), rapid walking speed (61%), 6-minute walk distance (82%), and daily step activity (121%) following underwater treadmill training. Effect sizes (*Partial* η^2) for these six variables ranged from .50 to .84, indicating that the magnitude of the training effect was medium to large.

Table 4

Descriptive Statistics for Pre- and Post-Training Values of Leg Strength, Balance, WISCI-II, Preferred Walking Speed, Rapid Walking Speed, 6-Minute Walk Distance, and Daily Step Activity (N = 11*)*

	Pre-training		Post-training	
Variable	*M*	*SD*	*M*	*SD*
Leg strength (N kg^{-1})	13.17	3.19	20.69	5.18
Balance	23.55	11.74	32.82	13.37
WISCI-II	12.36	3.85	13.55	4.11
Preferred walking speed (m s^{-1})	0.41	0.27	0.55	0.28
Rapid walking speed (m s^{-1})	0.44	0.31	0.71	0.40
6-minute walk distance (m)	97.3	80.2	177.0	122.33
Daily step activity (one leg)	593	782	1310	1258

Note. WISCI-II = Walking Index for Spinal Cord Injury

Table 5

Repeated-Measures ANOVA Results for Leg Strength, Balance, WISCI-II, Preferred Walking Speed, Rapid Walking Speed, 6-Minute Walk Distance, and Daily Step Activity

Dependent Variable	*F*	*p*	*Partial* η^2	*Power*
Leg strength	53.83	< .001*	.84	1.00
Balance	18.47	.002*	.65	.97
WISCI-II	3.37	.096	.25	.38
Preferred walking speed	18.47	.002*	.64	.97
Rapid walking speed	17.51	.002*	.64	.96
6-minute walk distance	10.41	.009*	.51	.83
Daily step activity	10.21	.01*	.51	.82

Note. *df* = (1, 10) for each *F* test; * = $p < .05$; *Partial* η^2 = effect size.

Post-hoc analyses were conducted to evaluate overall strength training responses of both legs, as well as specific lower-extremity muscle groups. Prior to training, the average difference in strength between the stronger and weaker legs was 33%, whereas after training, a 22% mean difference in strength between the stronger and weaker legs was detected. While a significant main effect for strength was observed between stronger and weaker limbs $F(1,10) = 6.29$, $p = .03$, *Partial* $\eta^2 = .39$, power = .62, no significant interaction was observed with respect to time, $F(1, 10) = 0.13$, $p = .73$, *Partial* $\eta^2 = .01$, power = .06. This indicates that there was no difference in the training response between the stronger and weaker leg, i.e., both legs displayed similar gains in muscle strength following underwater treadmill training. As shown in Figure 1, strength gains of 51% and 65% were measured in the stronger and weaker leg, respectively.

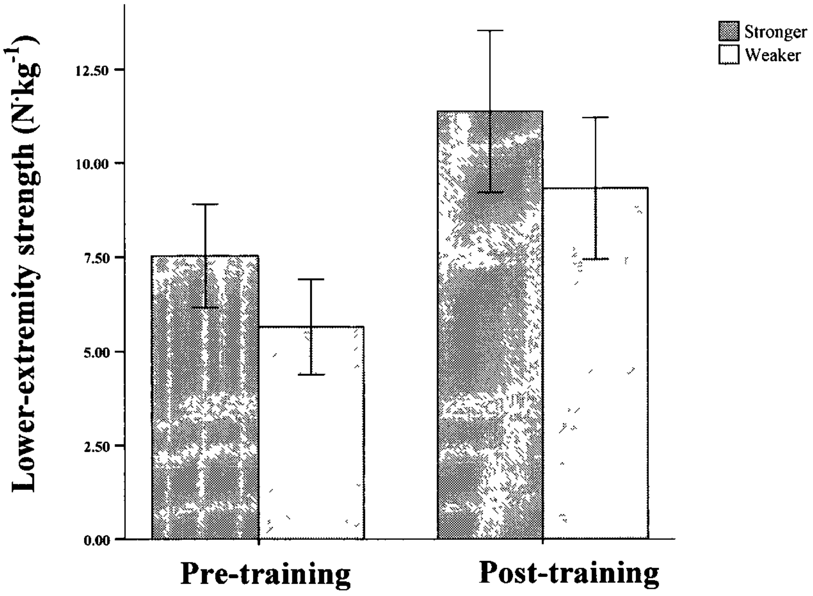

Figure 1. Changes in lower-extremity strength of the stronger and weaker leg following underwater treadmill training.

Another two way repeated measures ANOVA was performed to compare strength gains (pre-training, post-training) for each muscle group (hip extensors, hip flexors, hip abductors, knee flexors, knee extensors, and ankle dorsi and plantar flexors). This analysis revealed no significant interaction between time (pre- and post-training) and muscle group, *F*(2.39, 23.89) = 3.11, *G-G p* = .06, *Partial* η^2 = .24, power = .59, indicating that all muscle groups improved in a similar fashion as a result of underwater treadmill training. Figure 2 illustrates strength gains achieved for the seven muscle groups. Relative gains in muscle strength ranged from 32% for the knee flexors to 95% for the hip flexors.

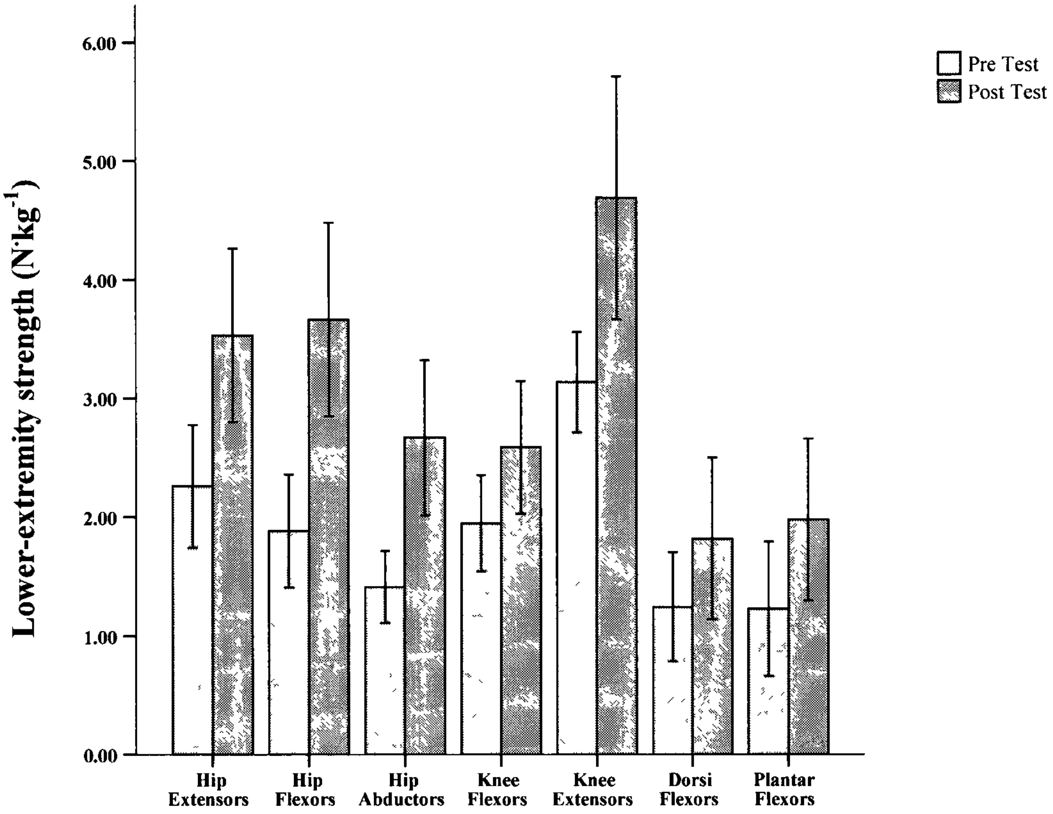

Figure 2. Strength gains achieved in each lower-limb muscle group following underwater treadmill training.

Biweekly changes in preferred walking speed were characterized using trend analysis. Results from this analysis demonstrated that a linear trend, $F(1, 10) = 16.68$, $p = .002$, provided the best statistical fit for these data when compared to the fit provided by the application of quadratic or cubic trend-fitting techniques. Figure 3 illustrates the linear trend between time and preferred walking speed.

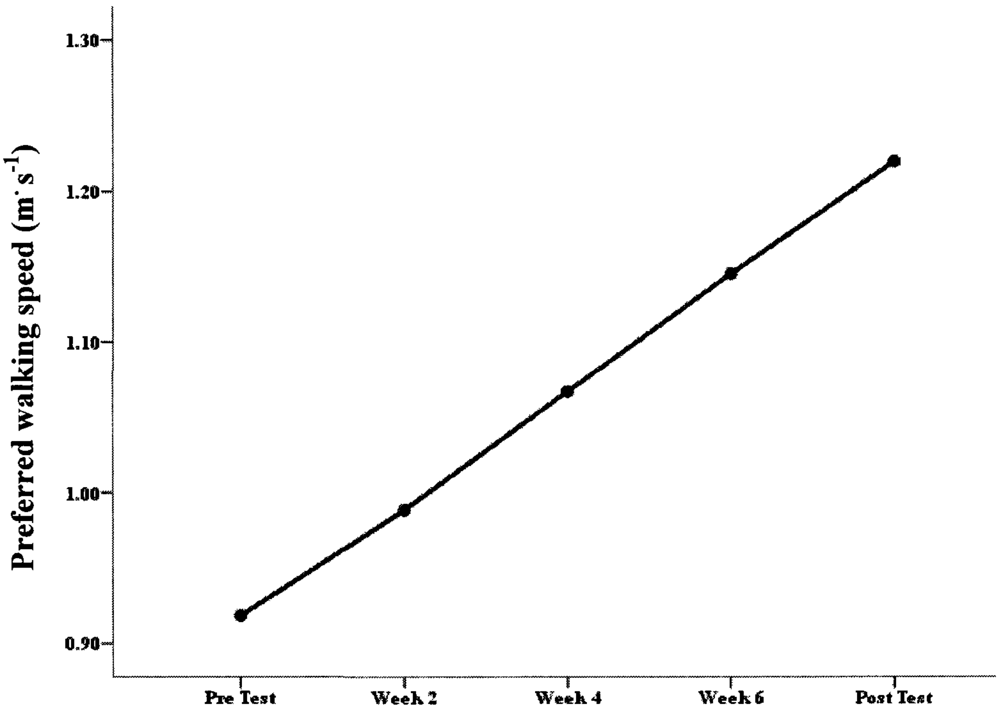

Figure 3. Biweekly changes in preferred walking speed.

Discussion

Contemporary neuroscientists have explored the role of the spinal cord in initiating and controlling complex motor patterns, such as walking. The basic premise of this approach is that the process of recovery of walking is enhanced not only by the presence of spared neural pathways, but also by the ability of the spinal cord to respond to specific afferent input. Seminal work in this area was conducted by Lovely, Gregor, and Edgerton (1986), who provided trunk support and manual assistance to cats with complete SCI while walking on a treadmill. The cats in this experiment demonstrated volitional stepping in the absence of upper motor neuron transmission and displayed increased cadence and step length in response to modifications in treadmill speed. These observations suggest that the cat spinal cord responded to afferent signals triggered by stimulation of proprioceptors, stretch receptors, or cutaneous receptors located in the periphery. Regardless of the source of afferent impulses, these findings are consistent with the idea that the sensory-motor feedback loop below the spinal lesion remains intact following SCI and may have the capacity to generate motor responses. This work has been supported by other investigators (Dietz & Duysens, 2000; Hodgson, Roy, Leon, Dobkin, & Edgerton, 1994; Van de Crommert, Mulder, & Duysens, 1998) and provides the foundation for conducting the present study, which explores the use of underwater treadmill training in adults with incomplete SCI.

The importance of achieving the highest possible level of physical function and mobility takes on a heightened sense of importance when cast against the secondary consequences of physical inactivity in the SCI population. Immobility has been associated with skin breakdown and pressure sores, osteoporosis, muscle atrophy, respiratory and cardiovascular problems, urinary tract infections, and a variety of comorbidities associated with diminished health and decreased life span (McDonald & Sadowsky, 2002; Myers, Lee, & Kiratli, 2007). According to McDonald and Sadowsky (2002), physical exercise can induce muscle hypertrophy and may facilitate regeneration and reorganization of neural pathways. These researchers suggested that even if muscle or nerve recovery is minimal following SCI, health benefits can be secured by engaging in physical activity. In contrast, the use of pharmaceutical interventions to recover physical function and walking ability has met little success (Barbeau & Norman, 2003; Dietz, Colombo, Jensen, & Baumgartner, 1995).

Building upon the research by Lovely et al. (1986), treatment of SCI in humans has primarily focused on providing partial body weight support with manual assistance or using robotic aids to move the lower limbs. Both of these movement-based therapies attempt to retrain the spinal cord to initiate lower-extremity motion by exposing receptors in the muscles, joints, and skin of the legs to specific types of stimulation to produce the desired motor output (Harkema et al., 1997; Maegele et al., 2002). While promising results have emerged from using these rehabilitative approaches, a variety of drawbacks exist which can limit the extent of recovery experienced by patients attempting to achieve useful levels of function. The most frequently-cited concerns include adverse cardiovascular responses to positional changes and body harnessing (Krassioukov & Harkema, 2006), decreased metabolic challenges and altered muscle activation patterns associated with DGO training (Israel et al., 2006), difficulty in achieving appropriate manual assistance during BWSTT (Galvez et al., 2007), and discomfort associated with the use of body harnessing systems. Against this backdrop, the current study represents the first-known attempt to quantify the effects of underwater treadmill training (UTT) on lower-extremity strength, balance, and community mobility in adults with incomplete SCI. Viewed in concert, findings from this project indicate that UTT resulted in statistically significant and meaningful improvements in nearly all primary outcome measures of physical function and walking status.

Lower-extremity strength. Data from the current study indicate that UTT produced significant improvements in leg strength across muscle groups. Post-hoc analyses also revealed that individual muscle groups contributed in a similar manner to the overall increase recorded in lower-limb strength. In addition, the resistance provided by walking in the water was sufficient to strengthen both the stronger and weaker legs of our participants.

It is difficult to compare lower-extremity strength values measured in the present investigation with data collected in other investigations because previous researchers have employed scale-based measures of muscle strength (Ditunno & Scivoletto, 2009; Dobkin et al., 2006; Geisler et al., 1991). However, it is possible to compare strength measures of individual muscle groups assessed in our sample of young and middle-aged adults with SCI (mean age = 48 years; range = 23 to 62 years) with strength thresholds required for elderly adults (*n* = 49; age range = 81 to 89 years) to achieve functional independence in activities of daily living (Hasegawa, Islam, Lee, Koizumi, Rogers, & Takeshima, 2008). Table 6 lists the strength thresholds for hip flexors, hip extensors, knee flexors, knee extensors, and ankle dorsiflexors reported by Hasegawa et al. and pre- and post-training muscle strength values obtained in the present study.

Table 6

Comparison of Leg Strength Requirements for Functional Independence in Elderly Adults andLleg Strength Observed in the Current Sample of Young and Middle-Aged Adults with Spinal Cord Injury

	Hip Flexors	Hip Extensors	Knee Flexors	Knee Extensors	Ankle dorsiflexors
Hasegawa et al. (2008) thresholds $N \cdot kg^{-1}$	2.3	1.7	.07	2.8	2.8
SCI UTT Study Pre-Training $N \cdot kg^{-1}$	1.88	2.26	1.95	3.13	1.24
SCI UTT Study Post-training $N \cdot kg^{-1}$	3.53	3.66	2.58	4.69	1.82

When relative muscle strength values found in Table 6 were summed, overall pre-training leg strength for participants in the current investigation was 108% of the total leg strength value calculated from data provided by Hasegawa and colleagues (2008). This implies that the overall leg strength of our sample of young- and middle-aged adults with SCI barely exceeded the minimal strength requirement for much older adults to perform independent self-care and living tasks. In contrast, the summed post-training leg strength of adults in the present study was 168% of the minimal leg strength requirement reported by Hasegawa et al. (2008), reflecting a much greater likelihood of self-care independence.

The practical impact of lower-limb strength gains achieved in the current project is related to the association between lower-extremity strength and the retraining of walking following SCI. Previous research has identified recovery of leg strength as the best predictor of functional ambulation following SCI (Kim et al., 2004). Walking behavior does not emerge until adequate muscle strength is available to provide body weight support and propel the body forward. To compensate for muscle atrophy which occurs following spinal cord damage, more motor units are recruited than would normally be needed to perform daily tasks requiring submaximal efforts, resulting in a greater energy demand which can lead to early fatigue. The increase in muscle recruitment efforts typically occurs in higher- threshold motor units which usually remain inactivated during activities such as slow walking. These higher-threshold motor units also fatigue rapidly due to their inability to support metabolic activity through oxidative phosphorylation. Conversely, interventions like UTT, which feature sustained muscle activity, counter muscle atrophy, and increase reliance on lower-threshold motor units, would be expected to exponentially lengthen walking duration and raise overall step activity (Lin, 2003).

Balance. As assessed by the Berg Balance Scale, balance was significantly improved following UTT. On average, participants increased their scores on the BBS by nine points. According to the developers of this balance assessment instrument, a change of eight points is required to observe a genuine change in function (Berg, Maki, Williams, Holliday, & Wood-Dauphinee, 1992).

Balance deficits have been associated with limited functional ambulation following SCI (Datta, Lorenz, Morrison, Ardolino, & Harkems, 2008). While improvement in balance has been associated with recovery of walking, challenges to balance have not consistently been a feature of BWSTT and DGO therapy, primarily because trunk and pelvic support are provided. On the other hand, the use of water as the unloading mechanism in underwater treadmill walking allows for greater excursions of weight shift and an increased reaction time as well as opportunities for small, ongoing balance adjustments to be made. Given the constraints associated with the use of BWSTT and DGO training, little is known regarding improvements in balance resulting from both types of movement therapy. However, in a case study by Behrman and Harkema (2001), the featured subject, a 43 year-old male (injury at C_6; AIS D classification) progressed from BWSTT to overground training and exhibited a 23% increase in BBS score. When compared to the 13% increase in BBS score noted in the current investigation, the greater improvement in BBS score displayed by the patient in the Berhman and Harkema (2001) study may have been linked to a longer training period (11 versus 8 weeks) and shorter post-injury time frame (8-months versus 5-years) that is within the range of expected recovery from SCI.

WISCI-II. As evaluated by the WISCI-II, walking capacity was unaffected by UTT. This finding is consistent with results of Wirz et al. (2005), who reported no change in WISCI-II scores among 20 male and female adults with incomplete SCI (AIS C and D) who underwent 8-weeks of DGO training. It should be noted, however, that other measures of walking ability, such as gait velocity and endurance, were improved following robotic therapy. Similarly, preferred and maximal walking speeds, 6-minute walk time, and daily step activity increased as a result of underwater treadmill training in the present study, but no improvement in the WISCI-II score was detected.

One potential explanation for the stability in walking capacity observed in the current project is that the length of the training program may have been insufficient to produce measurable changes in the use of walking aids, orthoses, or external physical assistance. It is possible that hesitation to wean away from the security provided by ambulatory aids may have also contributed to the lack of change in WISCI-II score. While many persons with SCI can walk with less external aid than is typically used, doing so can result in a slower walking velocity and lead to greater fatigue (Kim et al., 2007). Consequently, future interventions may need to consider evaluating walking capacity at higher WISCI-II ratings when assessing the impact of therapeutic interventions on walking capacity in persons with SCI.

Walking speed. Significant increases in walking speed occurred following UTT. Compared to pre-training values, preferred and rapid walking speeds increased by an average of 0.14 and 0.27 $m \cdot s^{-1}$, respectively. The magnitude of the increase in preferred walking speed was slightly greater than that reported by Wirz et al. (2005) (0.11 $m \cdot s^{-1}$) after an 8-week program of DGO training involving 20 adults with incomplete SCI.

Recent work has demonstrated the existence of a curvilinear association between walking speed and the number of daily steps taken in home and community settings in adults with SCI (Stevens, Caputo, Fuller, & Morgan, 2010). Findings drawn from this cross-sectional report of 21 adults with incomplete SCI report indicated that once walking velocity exceeds ~ 0.42 $m\ s^{-1}$, greater increases in daily steps are achieved with relatively small increments in walking velocity. In the current study, mean pre- and post-training preferred walking speeds were 0.41 $m \cdot s^{-1}$ and 0.55 $m \cdot s^{-1}$, respectively. Based on the walking speed-step activity relationship established by Stevens and colleagues (2010) (see Figure 4), this training-related increase in freely-chosen walking speed should theoretically result in a markedly higher daily step count level. Based on data presented in Figure 4, it can be roughly estimated that an average increase in daily step count of about 875 steps would be realized if preferred walking speed rose from 0.41 m·s^{-1} (pre-training value) to 0.55 m·s^{-1} (post-training value). Interestingly, this predicted gain in daily step count comports reasonably well with the actual mean increase of 717 steps per day observed following UTT.

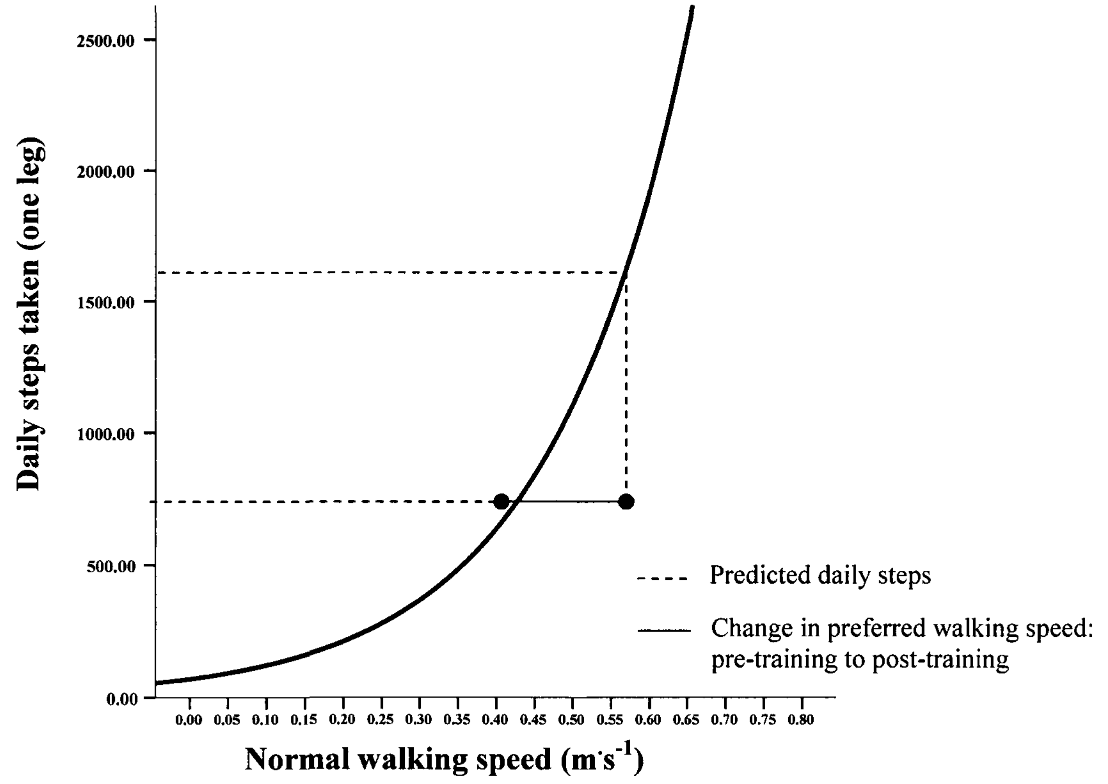

Figure 4. Predicted increase in daily step activity as a function of actual changes in preferred walking speed following underwater treadmill training. Walking speed-step curve drawn from the work of Stevens, Caputo, Fuller, & Morgan, 2010.

Six-minute walk test. Data from the current project revealed an 82% increase in 6-minute walk distance was observed following 2-months of UTT. The magnitude of this improvement in walking endurance is substantially greater than the 53% increase in 6-minute walk distance reported by Wirz et al. (2005) in 20 persons with incomplete SCI who completed an 8-week DGO training incorporating three therapy sessions per week. In absolute terms, the improvement in distance covered during the 6-minute walk test was nearly 80 meters, which is only 13 yards shy of the length of a football field.

The observed improvement in 6-minute walk distance is likely a function of both central and peripheral adaptations to the underwater treadmill training program. A primary central adjustment to endurance training is an expanded stroke volume, which increases maximal aerobic power ($V0_2$ max). Peripheral training adaptations include increases in mitochondrial capacity, muscle capillarization, and fat and carbohydrate oxidation, all of which contribute to an expanded arteriovenous oxygen difference and greater aerobic production of adenosine triphosphate (ATP) (McArdle, Katch, & Katch, 2001). An improvement in walking economy and an increased ability to incur a higher percentage of $V0_2$ max may have also contributed to the greater distance covered during the 6-minute walking test.

Daily step activity. A substantial increase in daily step activity occurred as a result of underwater treadmill training. On average, participants more than doubled their average daily step activity in home and community settings. Participants in the current study exhibited a mean daily step count of 593 steps prior to training, with individual step count values ranging from 15 to 2760 steps. In contrast, Bowden and Behrman reported a mean daily step count of 1604 steps (range = 68 steps to 4468 steps) for 9-participants (ages 21 years to 59 years) with incomplete SCI. Although our sample of adults with SCI were less ambulatory compared to participants in the Bowden and Behrmen report, the wide range of individual step count activity displayed in both studies clearly demonstrates a pronounced heterogeneity in the typical walking activity of adults with incomplete SCI that may be related to factors such as the extent of neural sparing, residual leg strength, opportunities to engage in physical activity, or other intrinsic and extrinsic factors related to recovery of walking.

When considering the health benefits of walking, it is important to recognize that health-related cutpoints for daily step activity have yet to be established for adults with SCI. When compared to either the general adult activity guideline of 10,000 steps per day established by the Centers for Disease Control and Promotion (2007) or step count guidelines for sedentary behavior (< 5,000 steps per day) published by Tudor-Locke and Bassett (2004), it is clear that participants in the current investigation exhibited low levels of ambulatory physical activity which may elevate the overall health risk in this population. However, the large relative increase in walking activity documented in the present investigation represents a meaningful gain in functional mobility and a higher overall level of energy expenditure, two outcomes that, if maintained over time, might be expected to lower the risk of morbidity and mortality from cardiovascular disease and other lifestyle-related health conditions.

Underwater treadmill training: body weight unloading. During underwater treadmill training, levels of body weight support were individually selected for each participant based on the amount of aid needed to maintain an upright position with maximal levels of hip and knee extension and guidance provided in the literature regarding appropriate ranges for partial body weight support training. In a study examining the effects of body-weight unloading and walking speed on changes in gait parameters in healthy adult males, van Hedel et al. (2006) proposed that body weight unloading should not exceed 75% and that participants should walk at a speed of at least

2.5 km·h^{-1} (0.69 m·s^{-1}), as this would produce a gait pattern closely resembling normal walking. However, these researchers also stated that these training parameters might be too intense for individuals with severe motor impairments and that functional improvement could occur at slower speeds or at higher levels of body weight support (van Hedel, 2006). An overview of studies employing BWSTT reveals that body weight unloading percentages have been set at 32% (Gardner, Holden, Leikauskas, & Rrichard, 1998), 37% (Wirz et al., 2005), 40% (Dobkin et al., 2003; Protas, Holmes, & Qureshy, 2001) and 80% (Wirz, Colombo, & Dietz, 2001) of land body weight. While body weight unloading is a critical training component in the facilitation of walking for persons with SCI, bearing weight is also a necessary stimulus to produce the neuromuscular adaptations required to foster improved ambulation (Fouad & Pearson, 2004). The kinematics of walking, for example, are influenced by load-bearing, insofar as the duration of the step cycle decreases and approaches a more normal range as weight support increases (Edgerton & Roy, 2009). Because persons with SCI display a longer step cycle duration, it is critical to provide the relative level of body weight unloading needed for walking, while facilitating the afferent signaling necessary to stimulate improvement in walking ability. The average level of body weight unloading recorded for participants in the present investigation was 38% of land body weight (range = 30% to 47%), a value similar to that employed by other BWSTT researchers (Wirz et al., 2005; Dobkin et al., 2003; Protas et al., 2001). Maintaining a static percentage of support throughout UTT allowed for the implementation of graduated increases in velocity, a key variable in replicating normal gait kinematics (van Hedel et al., 2006) and a factor associated with greater walking activity in home and community environments.

Underwater treadmill training: Cardiovascular response to training. Because of the partial loss of sympathetic functioning, persons with SCI exhibit lower levels of epinephrine and norepinephrine (Schmid et al., 1998). The relative lack of freely-circulating catecholamines limits the degree and rate of cardiac acceleration as exercise intensity increases. The difficulty in producing an appropriate cardiovascular response during physical activity is further magnified by diminished muscle activity in the lower extremities, which limits the return of venous blood to the heart (Schmid et al., 1998). Consequently, persons with SCI display a limited capacity for exercise due to a lower stroke volume and a restricted ability to increase heart rate. However, exercising in an aquatic environment can mitigate some of the reduction in cardiovascular function observed in the SCI population because of the positive effect of hydrostatic pressure in raising central blood volume.

Because heart rate was monitored during UTT, a post-hoc assessment of heart rate response to training was conducted. Figure 5 depicts changes in average heart rate values during Weeks 2 and 3 (line a), Weeks 4 and 5 (line b), and Weeks 6 and 7 (line c). As shown in Figure 5, a classic training response was observed, as exemplified by statistically significant ($p < .05$) reductions in heart rate during Weeks 2 and 3 (7.1%), Weeks 4 and 5 (10.7%), and Weeks 6 and 7 (15.5%). In interpreting these data, it bears mentioning that the decrease in heart rate observed in Weeks 4 and 5 and Weeks 6 and 7 occurred in conjunction with a 10% increase in walking speed over the previous 2-week period. A particularly striking example of the impact of UTT on exercise heart rate can be seen when comparing mean heart rate values at the end of Week 7 with those recorded during all of Week 4. As shown in Figure 5, the mean heart rate value measured on the final day of Week 7 was actually lower than values recorded during all of Week 4, even though walking speed was 10% faster in Week 7 compared to Week 4.

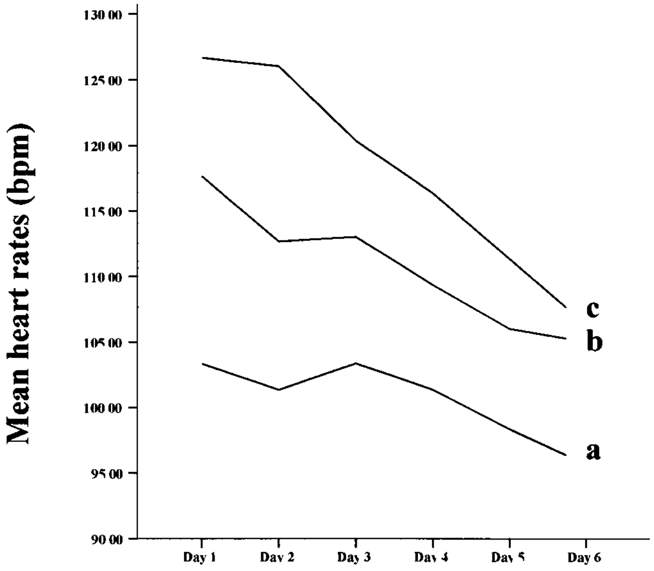

Figure 5. Mean heart rates during a) Weeks 2 and 3, b) Weeks 4 and 5, c) Weeks 6 and 7 of the underwater treadmill training program.

Perceived benefits from participating in the underwater treadmill training program. In addition to quantifying training-related changes in leg strength, balance, and functional mobility, participants were asked to provide a written summary of their perceptions of benefits gained from participating in the underwater treadmill training program. As outlined in Table 7, these perceptions were grouped into four major categories encompassing improvements in functional mobility, functional independence, general health, and mental well-being. As an illustration of the enthusiasm displayed by study participants, all of them digitally recorded their training sessions and distributed photographs and/or videos taken while walking on the treadmill. In addition, several participants created websites or posted YouTube videos of their treadmill walking sessions.

Table 7

Participants' Perception of Changes Associated with Underwater Treadmill Training

Perceived Change	Examples
Improved Functional Mobility	Improved balance
	Improved ability to climb stairs
	Decreased use of assistive devices
	Increased stability
	Ability to stand independently
	Fewer falls
	Less time spent in a wheelchair
	Faster
	Ability to walk in the yard
Greater Independence	Ability to transfer independently
	Eliminated the use of a sliding board
	Ability to reach for objects
	Ability to pick objects up from the floor
	No longer needing assistance during the night
	Ability to get up from the floor
Better General Health	Increased endurance
	Increased strength
	Increased muscle bulk
	Weight loss
	Fitter
	Decreased stress
Improved Mental Well-Being	Increased confidence
	Decreased fear
	More comfortable
	Loss of heavy feeling
	When I dream I am walking

The positive perceptions of benefits gained from engaging in UTT were further supported by written statements provided by a cross-section of participants who were interviewed for a campus newspaper article. Below is a sampling of quotations from these participants.

"Even though the medical professionals at the time, said, 'Well you'll never get up and walk again,' every time I get up, I'm reminded, 'Ha ha, proved you wrong."

"At the beginning, I'd get my feet crossed up frequently, and I don't do that anymore. So there's been an increase in stability and control. In (the tank), you don't have the fear of falling over and breaking a hip, or doing something that you'd let be in a hospital for a long period of time.'

"You feel good. You feel comfortable. You feel like you can handle whatever it is you've got to deal with. As long as you just have something that you're reaching for, you always push a little harder."

"When I first started the program, I could barely get around when I went shopping, now I can go 20 minutes before I need to sit."

"The therapy has made it so that I can go to the recreation-center pool in town and train on my own. I'm strong enough to go it on my own and work out."

"If I were to listen to what they had told me, I'd still be lying in the hospital bed or in a nursing home. With spinal cord injuries, you're like a child; you have to learn to do everything again. If you don't keep moving something, it'll quit working."

"I've notice more of an improvement in my walking since I've been doing the treadmill underwater than I have anything."

In conclusion, findings from this investigation have clearly demonstrated the efficacy of underwater treadmill training in promoting improved functional mobility in adults with incomplete spinal cord injury who are past the phase of expected recovery. More specifically, statistically significant increases of moderate to large magnitude were observed in lower-extremity strength, balance, and various indices of walking performance following 8-weeks of training incorporating personalized levels of body weight support and gradual and systematic increases in walking speed and duration. From a qualitative standpoint, a number of perceived benefits related to mobility, independence, and general and mental health and well-being were also identified by study participants.

Because almost no information currently exists regarding the effectiveness of UTT in clinical settings, multisite trials should be conducted to establish the reliability and validity of this water-based therapy using larger sample sizes and appropriate control groups. In addition, refinement of key training components (e.g., intensity, frequency, and intensity of training, relative level of body weight support) should be considered in future studies to better tailor underwater treadmill exercise to specific physically-challenged populations. The relationship between time of injury onset and the effectiveness of UTT and the impact of UTT on quality of life measures are topics which also deserve future scrutiny.

As a final note, perhaps the most promising element of this approach to gait retraining is the availability of water, which may improve access and maximize rehabilitation potential beyond the research and clinical environment. Viewed in this light, greater efforts should be undertaken to translate the laboratory methodology described in this report into usable programs that community-based groups and recreational facilities can employ to improve the walking ability and physical function of persons with severe gait disorders.

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APPENDICES

Appendix A

MTSU Institutional Review Board Approval: Study 2

Sandy Stevens & Dr. Don Morgan
Department of Health and Human Performance
sstevens@tnstate.edu, dmorgan@mtsu.edu

Protocol Title: "The Effects of Underwater Treadmill Training on Aerobic Fitness, Leg Strength, Balance, Mobility and Quality of Life in Adults with Incomplete Spinal Cord Injuries"
Protocol #: 10-008

Dear Investigators,

The MTSU Institutional Review Board, or a representative of the IRB, has reviewed the research proposal identified above. The MTSU IRB or its representative has determined that the study poses minimal risk to participants and qualifies for an expedited review under 45 CFR 46.110 Category 4.

Approval is granted for one (1) year from the date of this letter for 30 participants.

According to MTSU Policy, a researcher is defined as anyone who works with data or has contact with participants. Anyone meeting this definition needs to be listed on the protocol and needs to provide a certificate of training to the Office of Compliance. If you add researchers to an approved project, please forward an updated list of researchers and their certificates of training to the Office of Compliance before they begin to work on the project.

Any change to the protocol must be submitted to the IRB before implementing this change. Additionally, any unanticipated harms to participants or adverse events must be reported to the Office of Compliance at (615) 494-8918.

You will need to submit an end-of-project report to the Office of Compliance upon completion of your research. Complete research means that you have finished collecting and analyzing data. Should you not finish your research within the one (1) year period, you must submit a Progress Report and request a continuation prior to the expiration date. Please allow time for review and requested revisions. Your study expires July 23, 2010.

Also, all research materials must be retained by the PI or faculty advisor (if the PI is a student) for at least three (3) years after study completion in a secure location. Should you have any questions or need additional information, please do not hesitate to contact me.

Sincerely,
Tara M. Prairie
Research Compliance Officer

Appendix B

Informed Consent Document for Research: Study 2

Middle Tennessee State University Institutional Review Board
Informed Consent Document for Research

Principal Investigator: Sandy Stevens **Date: 7/15/09**
Study Title: The effects of underwater treadmill training on aerobic fitness, leg strength, balance, mobility, and quality of life in adults with incomplete spinal cord injuries

Institution: Middle Tennessee State University

This informed consent document applies to adults

Name of participant ______________________________ Age __________

The following information is provided to inform you about the research project and your participation in it Please read this form carefully and feel free to ask any questions you may have about this study and the information given below You will be given an opportunity to ask questions, and your questions will be answered. Also, you will be given a copy of this consent form

Your participation in this research study is voluntary You are also free to withdraw from this study at any time In the event new information becomes available that may affect the risks or benefits associated with this research study or your willingness to participate in it, you will be notified so that you can make an informed decision whether or not to continue your participation in this study

1. **Purpose of the study:**
   You are being asked to participate in a research study because of your experience with spinal cord injury The purpose of this study is to determine if underwater treadmill training will improve your ability to walk

2. **Description of procedures to be followed and approximate duration of the study:**
   As a participant in this study, you will be asked to complete a pre-test, eight weeks of training using the underwater treadmill, and a post-test The pre-test will include an overground walk of approximately 15 feet during which your walking speed will be measured Following this walk, you will walk around a gymnasium floor for up to 5 minutes During this walk, we will collect your expired air (you will be breathing into a mask) to measure your energy expenditure and endurance Next, we will measure your standing balance using specialized equipment To complete the testing, your lower-extremity strength will be measured using a small portable dynamometer You will also be asked to wear a step activity monitor which will count the number of steps taken over a 7-day period and complete a standardized questionnaire to assess quality of life The entire testing session will last approximately two hours and you will be provided with rest breaks in-between testing stations Once the pre-testing is completed, you will begin eight weeks of underwater treadmill training During the training period, you will be expected to attend three training sessions per week A session will consist of three walks on the underwater treadmill that will last 5 to 10 minutes in length Over the 8-week period, the intensity, duration, and water height will be adjusted to gradually increase training volume The final phase the project will be to complete post testing which will be a repeat of the pre-test

3. **Expected costs:**
   There are no costs associated with this study

4. **Description of the discomforts, inconveniences, and/or risks that can be reasonably expected as a result of participation in this study:**
   There are no known risks involved in the collection of this data Walking speed will be assessed under normal indoor walking conditions over level ground The endurance walk will be conducted at a comfortable walking speed The muscle testing will feature a noninvasive procedure requiring you to exert your best effort Balance will be assessed on a platform with handles available, if needed The step activity monitor is a lightweight apparatus attached to the right ankle by an adjustable Velcro strap The underwater treadmill provides a safe environment for walking

[illegible]

5. **Unforeseeable risks:**
As in any aquatic environment, the floor may become slippery when wet There is water tile surrounding the treadmill to reduce slipping Towels are also available in minimize this risk

6. **Compensation in case of study-related injury:**
No compensation will be provided

7. **Anticipated benefits from this study:**
   a) The potential benefits that may result from this study are related to mobility outcomes for adults with spinal cord injuries. Persons with spinal cord injuries are often restricted to a sedentary lifestyle because of difficulty with walking Limited ambulation in this population may be related to diminished strength, balance and walking speed, both of which have been observed in this population If interventions can be identified to improve these skills, improvements in independent walking may follow

8. **Alternative treatments available:**
No alternative treatment is available

9. **Compensation for participation:**
No monetary compensation will be provided

10. **Circumstances under which the Principal Investigator may withdraw you from study participation:**
You may be withdrawn from the study if you are not able to complete any of the tests associated with this investigation

11. **What happens if you choose to withdraw from study participation:**
Participation in this project is completely voluntary Participation may be discontinued at any time without risk of prejudice or penalty.

12 **Contact Information.** If you should have any questions about this research study or possibly injury, please feel free to contact Sandy Stevens at (615)963-7490 or my Faculty Advisor, Don Morgan at (615)898-5549 For additional information about giving consent or your rights as a participant in this study, please feel free to contact the Office of Compliance at (615) 494-8918

13. **Confidentiality.** All efforts, within reason, will be made to keep the personal information in your research record private but total privacy cannot be promised Your information may be shared with the MTSU University Institutional Review Board or if you or someone else is in danger or if we are required to do so by law

STATEMENT BY PERSON AGREEING TO PARTICIPATE IN THIS STUDY

I have read this informed consent document and the material contained in it has been explained to me verbally. All my questions have been answered, and I freely and voluntarily choose to participate.

Date Signature of patient/volunteer

Consent obtained by

Date Signature

Printed Name and Title

Adapted from Vanderbilt University

CHAPTER IV

PROJECT CONCLUSIONS

Approximately 259,000 people in the United States are currently living with spinal cord injury (SCI), and the majority of these individuals are otherwise healthy males who are 40 years of age or younger (National Spinal Cord Injury Statistics Center, 2009). Due to advances in the acute and long-term management of this health condition, the longevity of persons with SCI has increased over the past decade (Krause & Broderick, 2005). However, the reduction in physical activity which typically accompanies SCI contributes to the development of a host of secondary health consequences, including an increased risk of coronary heart disease (Lavis, et al., 2007; Myers, Lee, & Kiratli, 2007). Consequently, an emerging area of research has been to develop effective strategies to enhance the recovery of walking and lessen the impact of physical disability following SCI. While activity-based therapies such as partial body weight support and robotic-assisted training currently exist to help persons with SCI regain some level of useful physical function and mobility, concerns related to body harnessing, the availability of multiple skilled therapists, high financial costs, and the generation of inappropriate muscle activation patterns have hindered the widespread use of these rehabilitative approaches in clinical settings.

In developing interventions to improve the ambulatory status of persons with SCI, it is essential to identify key determinants of community walking activity in this physically-challenged population. Hence, the main objectives of the first study of this dissertation project were to explore relationships among lower-extremity strength, preferred walking speed, and daily step activity and to quantify the combined effects of lower-limb strength and preferred walking speed on home and community walking activity in adults with incomplete SCI. Findings from this investigation, which featured 21 adults (17 males, 4 females; age = 39 ± 12 years; 3 ± 2 years post-injury) demonstrated that statistically significant relationships of moderate to strong magnitude (range = .74 to .87) were present among leg strength, normal walking speed, and daily step counts. Moreover, 83% of the explained variance in daily step activity was predicted from knowledge of lower-limb strength and freely-chosen walking speed. While the relationship between lower-extremity strength and daily step activity was linear, the association between preferred walking speed and daily step activity was curvilinear in nature, signifying that as walking speed increased, greater increments of daily step activity were observed. Taken together, these findings suggest that future research- and clinically-based efforts to enhance home and community walking following SCI should be directed towards increasing leg strength and preferred walking speed.

Based on findings from this initial investigation, a second study was conducted to quantify the effects of an 8-week underwater treadmill walking program on lower-extremity strength, balance, and various descriptors of walking performance in adults with incomplete SCI. Eleven adults (7 males, 4 females, age = 48 ± 14 years; 5 ± 8 years post-injury) completed an 8-week program of underwater treadmill training incorporating gradual and systematic increases in walking speed and duration. During training, the average body weight support provided by individually-determined water height levels was 38% of land body mass (range = 29% to 47%). Data analyses revealed that statistically significant and clinically meaningful improvements in leg strength, balance, normal and rapid walking speeds, 6-minute walk distance, and daily step activity. Trend analysis also indicated that preferred walking speed measured at biweekly intervals during the 2-month training program continued to increase in a linear pattern, with no evidence of a plateau effect.

Overall, the collective findings of this dissertation project provide support for the use of underwater treadmill training as an effective means of recovering walking ability and restoring functional mobility in adults with SCI. Future research in this area should focus on refining training parameters and protocols to further tailor the use of this activity-based therapy to various gait-impaired populations. In addition, the potential impact of underwater treadmill training on quality of life in persons who have experienced spinal cord injury should be examined. Concerted efforts should also be undertaken to conduct multisite clinical trials that feature the use of appropriate control groups. While underwater treadmill training is not meant to replace or substitute for other current gait retraining techniques, findings from the training study suggest that this type of water-based walking therapy has the potential to improve locomotor function, physical health, and life satisfaction in persons who have experienced severe neurological damage.

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APPENDICES

Appendix A

Review of the Literature

Introduction

Spinal cord injury is one of the most frequent and severe injuries treated in rehabilitation centers throughout the country (National Spinal Cord Injury Association, n.d.). Typically, damage to the spinal cord is the result of trauma due to car accidents, gunshot accidents, sports accidents and falls, or diseases such as polio and cancer (National Spinal Cord Injury Association). Loss of motor and sensory function from spinal cord injury results from a disruption in the transmission of electrical signals which ascend and descend the spinal cord.

The spinal cord is a conduit through which motor and sensory information is transmitted between the brain and the body. This communication pathway allows the brain to monitor and respond to changes in the body's internal and external environment and to initiate and modify voluntary motion (Sheerin, 2004). The spinal cord is protected by rings of bone, or vertebrae, which surround the cord and constitute the spinal column. In general, the higher the injury level in the spinal cord, the greater is the degree of physical dysfunction experienced (Sheerin).

The vertebrae and corresponding spinal cord segments are named according to their location. The eight spinal segments in the neck are collectively referred to as the cervical spine. Cervical spinal cord injuries typically lead to loss of function in both the arms and legs and result in quadriplegia (also known as tetraplegia). The 12 spinal segments in the chest are known as thoracic segments. The first thoracic segment (T_1) controls upper-extremity function, while the remainder of the thoracic segments contributes to trunk and lower-extremity involvement. An injury below T_1 will lead to loss of trunk and leg movement, while sparing function in the upper extremities. A person with this type of injury is referred to as paraplegic.

Besides a loss of sensation and motor function, individuals with spinal cord injuries may experience bowel, bladder, and sexual dysfunction (Sheerin, 2004). High-level (cervical) injuries can lead to the loss of autonomic functions such as breathing. In these cases, breathing aids such as mechanical ventilators or diaphragmatic pacemakers may be required (Sheerin). Other consequences of spinal cord injury include an inability to regulate blood pressure effectively, less intrinsic regulation of body temperature, a lack of sweating response below the level of injury, and chronic pain (Sheerin).

Traumatic SCI may result in complete or incomplete lesions of the spinal cord. A complete lesion is defined as an absence of all motor and sensory function below the site of injury. If any sensory and/or motor function is present below the affected neurological site, the injury is classified as incomplete (American Spinal Cord Injury Association, 2006).

Prevalence of Spinal Cord Injury

Approximately 400,000 individuals in the United States have experienced a spinal cord injury (National Spinal Cord Injury Statistics Center, 2009) and about 12,000 people sustain new injuries annually (Lavis et al., 2007). An estimated 60% of these individuals are 40 years old or younger and the majority are male (National Spinal Cord Injury Statistics Center, 2009). Since 1988, 45% of all spinal cord injuries have been classified as complete, while 55% have been designated as incomplete injuries (National Spinal Cord Injury Statistics Center). Only an extremely small percentage (0.90%) of persons with spinal cord injuries experience a full recovery (National Spinal Cord Injury Association, n.d.).

Of spinal cord patients who survive the first 24 hours, 85% will live at least 10 years (National Spinal Cord Association, n.d.). Until recently, the most common causes of death were related to respiratory or renal insufficiency (Myers et al., 2007). However, new treatment advancements have increased the life expectancy of persons living with SCI. Interestingly, as life expectancy has risen in this population, morbidity and mortality from coronary heart disease (CHD) have increased. Data from epidemiological studies indicate that CHD is a cause or contributing factor in nearly a quarter of all deaths for persons with SCI (Lavis et al., 2007). In individuals over 30 years old with SCI, CHD accounted for 46% of all deaths (Lavis et al.).

Acute Rehabilitation Following Spinal Cord Injury

Initial treatment for individuals experiencing SCI focuses on stabilization of the lesion to minimize spinal trauma. Once the lesion is stabilized, the condition is non-progressive. Hence, changes that occur in physical function over time are secondary and may be related to modifiable factors such as compliance with self-care protocols and lifestyle choices. During the early stages of recovery, an evaluation is made regarding the need for adaptations to the injury, including equipment related to mobility. Following this initial assessment, training in the use of appropriate devices is provided to facilitate the transition to a lifestyle of modified independence.

For the individual with SCI, the process of rehabilitation frequently begins immediately post-medical stabilization, prior to the resolution of spinal shock (i.e., inflammation of the spinal cord and surrounding tissue) and psychological acceptance of the injury. Because of restrictions on the number of treatment days allowed by third-party payers and the perceived need to return to independent living status in a timely fashion, opportunities for patients to engage in activities directed toward recovery and remediation are often limited. The number of treatment days for rehabilitation varies, but an average length of stay was 37 days in 2008, which is substantially lower than the mean length of 98 days reported 20 years ago (National Spinal Cord Injury Statistics Center, 2009).

Quality of Life

Given the complex interactions among mobility, health, and quality of life, it is not surprising that quality of life scores are lower for persons with SCI compared to able-bodied peers. In general, quality of life is viewed as optimal functioning at the highest level of independence (Falvo, 1999). Oleson (1990) described quality of life as the ability to participate in all domains of life that contribute to its richness. A healthy musculoskeletal system is fundamentally linked to an individual's ability to be mobile and actively participate in daily tasks necessary to maintain independence. Personal well-being and the health of many, if not all, body systems are negatively affected when mobility is impaired, leading to a continued downward spiral in health and ambulatory status. Secondary consequences and symptoms of SCI may include pain, fatigue, spasticity, obesity, and related diseases (Buchholz, McGillivray, & Pencharz, 2003).

In a longitudinal study of persons with SCI, it was reported that those with limited mobility were less satisfied with their lives than persons with no mobility limitations. Results from this investigation also showed that having a job significantly increased satisfaction among people with SCI and that employment was positively associated with independent ambulation (Krause & Broderick, 2005). Further analyses revealed that over time, individuals with SCI reported diminished satisfaction with their social lives, sex lives, and health, all of which are directly or indirectly associated with functional mobility (Krause & Broderick, 2005).

To summarize, persons with limited mobility following spinal cord damage typically experience limited independence and a host of secondary health consequences that result in a diminished quality of life. Rehabilitative interventions focus on adapting to changes in lifestyle and compensating for the loss of physical function. While these therapeutic approaches help to promote an independent lifestyle, they do not address the issues of recovery of lost physical function or the potential role of physical activity in promoting mobility or improving quality of life.

Physical Activity and Spinal Cord Injury

The reduction in physical activity observed after SCI has been attributed to a variety of factors, including psychological issues, lost motor function, and decreased accessibility to equipment, exercise facilities, and activity programs (National Center for Medical Rehabilitation Research, n.d.). Although greater emphasis has been placed on documenting improvements in health resulting from physical activity in persons with SCI, efforts to apply this evidence-based knowledge in clinical and community-based settings have not always been successful.

Health and functional benefits of physical activity in persons with SCI.

Research has shown that physical activity, even when induced by electrical stimulation, has the potential to lessen the effects of sedentary living and facilitate recovery of lost function in individuals with SCI. In work by Bickel, Slade, Warren, and Dudley (2003), for instance, electrical stimulation applied to muscles of varying composition in patients with spinal cord injuries improved muscle function as demonstrated by a reduction in foot drop and an increase in standing ability. Electrical stimulation of the leg muscles of spinal cord patients has also been shown to activate the physiologic muscle pump and prevent orthostatic hypotension, resulting in better tolerance to standing (Faghri & Yount, 2002). In patients with long-standing tetraplegia, dual energy x-ray absorptiometry (DEXA) revealed that lean body mass increased by 2% and body fat decreased by 1.9% following 8-weeks of electrically-stimulated leg cycling (Hjeltnes, etal., 1997). These changes in body composition were observed in the legs and the entire body, whereas no changes in lean body mass or body fat were noted in the unexercised upper extremities. Computerized axial tomography scans of the muscles supported the DEXA findings by indicating greater muscle mass and increased density in most of the stimulated muscle groups.

Improved oxygen diffusion and cardiorespiratory function have been reported in persons with spinal cord injuries following regular doses of physical activity. A significant increase in the diffusion of O_2 to the mitochondria of muscles has been noted in spinal cord patients who exercised using an upper-extremity ergometer (Fukuoka, Endo, Kagawa, Itoh, & Nakanishi, 2002). This finding suggests that training the upper extremities of spinal cord patients may enhance the health of these individuals by increasing O_2 availability. In considering heart and lung function in persons with SCI, Hooker and Scremin (1995) found that because of the sedentary lifestyle of individuals with SCI, most will experience muscle atrophy and autonomic dysfunction, both of which can contribute to low levels of aerobic fitness. In their study, spinal cord patients completed 12 weeks of electrically-facilitated leg cycling three times per week. These authors concluded that this mode of training improved cardiorespiratory fitness during peak and submaximal exercise. Elevated respiratory fitness was also observed in a study documenting vital capacity and dynamic ventilatory performance in spinal cord patients. In this report, the ventilatory capacity of the SCI group was severely reduced prior to the investigation compared to values noted for able-bodied participants. Following participation in a 6-week arm-cranking aerobic training program, ventilatory function in the SCI group was comparable to that of control participants (Silva et al., 1998).

Because of a diminished ability to perform weight-bearing activities, decreased bone mineral density is a major health concern for individuals with spinal cord injuries. Researchers quantifying the effect of spinal cord injury on bone mineral density have noted that rapid bone loss occurs during the first year following acute injury. Bone mineral loss is often apparent in bones undergoing the greatest mechanical stress prior to the injury, which are typically those loaded most frequently during ambulation (Kiratli, Smith, Nauenberg, Kallfelz, & Perkash, 2000). Aging also results in bone adaptation, with bone density showing a more rapid decline with the passing of time. Although the potential effects of specific interventions were not measured, it was suggested that physical activities which impose mechanical stress on the bones may interrupt the deterioration of bone density in persons with SCI (Kiratli et al.).

In considering the extent to which exercise poses a serious thermoregulatory challenge in individuals who have experienced spinal cord injury, Price and Campbell (1999) attempted to determine if the loss of sympathetic nervous system regulation caused adults with SCI-related paraplegia to exhibit a higher incidence of heat-related consequences during sports and exercise participation. Data from this study revealed that athletes experiencing paraplegia are at no greater risk of suffering the negative consequences of heat exposure compared to able-bodied athletes. Moreover, these investigators found that a positive association exists between heat-producing muscle mass and sweating capacity which results in thermal balance (Price & Campbell, 1999).

While improvements in physical performance are related to participation in physical activity programs, it is reasonable to question whether these improvements persist once the intervention has ceased. To address this issue, Gurney, Robergs, Aisenbrey, Cordova, and McClanahan (1998) quantified the residual effects of a 12-week training program incorporating functional electrical stimulation ergometry. Following 8-weeks of post-training inactivity, participants with SCI were able to partially maintain the strength and endurance acquired during the training phase of the program. Although speculative, it was suggested that the integration of physically-challenging activities into daily living routines enabled muscular and cardiorespiratory gains to remain elevated above baseline levels (Gurney et al.)

In addition to specific improvements in health and fitness measures, a moderately strong correlation exists between physical activity and quality of life in persons with SCI. In a recent study documenting this relationship, for instance, level of physical activity alone accounted for 57% of the variation in quality of life scores in adults with SCI (Stevens, Caputo, Fuller, & Morgan, 2008).

Assessment of Physical Activity in Persons with SCI

Recommendations established in the *2007 Physical Activity and Public Health: Updated Recommendation for Adults from the American College of Sports Medicine and* *the American Heart Association* (Haskell et al., 2007) identified physical activity as a key component of health promotion and disease prevention. This report also highlighted the need for increased physical activity in populations in which physical inactivity is prevalent, such as individuals with incomplete SCI who often spend extensive time in wheelchairs.

To comply with these recommendations, it is vital to accurately quantify daily physical activity in the SCI population. For ambulatory individuals with SCI, lightweight measurement instruments are now available which record and store ongoing physical activity in home and community environments. One such device is the OrthoCare Step Activity Monitor (SAM). The SAM is a micro-processor-driven accelerometer that measures walking activity in terms of both intensity and quality. The SAM has been validated for use by individuals with incomplete SCI. In a study by Bowden and Behrmen (2007), for example, the SAM was reported to be 97% accurate compared to hand-tallied step counts taken during 6- and 10-minute walk tests. These authors concluded that the SAM is an accurate and reliable device for capturing walking activity in individuals with incomplete SCI. Additional validation of the SAM was conducted in a published case study which reported 98% accuracy between manual step counts and those recorded using the SAM (Behrman et al., 2005).

Restoration of Walking Following SCI

The earlier sections of this review have identified the potential to enhance physical performance and enumerated a number of benefits associated with increasing physical activity levels following SCI. Perhaps one of the most obvious ways to achieve these goals is to improve walking ability. However, relatively little is known concerning the specific variables which underlie successful community walking levels in persons with SCI.

The decline in ambulatory function which often accompanies SCI can force a transition from unassisted locomotion to wheelchair use. Against the backdrop of technological advances, increased knowledge about neural regeneration and reorganization, and the unfavorable consequences of sedentary living, greater attention has recently been directed towards promoting the recovery of walking in individuals with SCI. To elaborate upon this clinical trend, the following section describes three therapeutic approaches which may hold promise in improving functional mobility in persons who have experienced spinal cord injury.

Body weight supported treadmill training (BWSTT). BWSTT is a rehabilitative strategy which has gained popularity among individuals with incomplete SCI. BWSTT is performed by supporting a portion of the person's body weight using a harness-counterweight system located over a motorized treadmill. In early studies, BWSTT protocols required therapist-assisted movement of the lower limbs and support of the trunk in patients with SCI. These techniques were found to be beneficial in facilitating stepping and replicating specific gait mechanics (Barbeau, 2003; Harkema, Hurley, & Patel, 1997; Visintin & Barbeau, 1989). In addition, BWSTT has been shown to facilitate walking in persons with incomplete SCI (Barbeau; Dobkin et al., 2006; Visintin & Barbeau). In a longitudinal study documenting the effects of 12 months of BWSTT, 13 of 14 chronic incomplete SCI (American Spinal Cord Injury Association Impairment Scale B and C) participants completed 144 training sessions. Following training, body weight support levels were reduced by 54% and participants increased their treadmill walking speed and distance by averages of 180% and 335%, respectively. Further analyses revealed that 6-participants improved their ability to walk overground. Eight months after the study was completed, overground walking scores remained stable, although a slight decline in treadmill walking ability was noted (Hicks et al., 2006).

Not all investigations have reported such positive outcomes following BWSTT. In a 2007 multicenter randomized study (Dobkin et al., 2007), 107 adults with incomplete SCI who were unable to walk were tracked over the first 12 weeks of rehabilitation. Participants were stratified into groups based on injury location and level of function and randomly assigned to treatment groups. In this experimental design, BWSTT was compared to traditional therapeutic interventions such as conventional overground walk training. While improvement was noted in both groups, there were no group differences in post-test scores on walking speed, leg strength, or the Function Independence Measure-Locomotion. In addition to group similiarities in outcome measures following 12 weeks of rehabilitation, no differences in walking ability, walking speed, or leg strength were noted at either 6- or 12-month follow-up sessions. It was concluded that participants displaying higher levels of physical function at the beginning of the study were likely to recover the ability to walk in community settings at velocities used by healthy individuals by 6-months, regardless of the type of intervention received (Dobkin et al., 2007).

Despite the potentially positive benefits of BWSTT, the practicality of employing this gait training approach in the clinical setting has been questioned. Inconsistent outcomes have been attributed to the skill of the therapists in facilitating stepping. For example, in a report examining manual assistance during BWSTT, it was found that less-experienced therapists demonstrated difficulty facilitating leg extension during stance and allowed toe drag during swing (Galvez et al., 2007). In addition, BWSTT has been described as physically demanding and labor-intensive, requiring up to three therapists to produce appropriate gait kinematics (Wirz et al., 2005).

Driven gait orthosis. Concerns that the implementation of BWSTT requires a number of highly trained therapists have caused researchers and clinicians to seek alternative methods of improving gait function in physically-challenged individuals. One such approach involves the use of a computer-controlled driven gait orthosis (DGO) which provides assisted locomotor training without manual facilitation. The DGO provides an exoskeleton for the lower extremities which assists the legs in moving through coordinated trajectories that mimic the kinematic motor patterns associated with walking. When combined with body-weight support, the DGO may facilitate a stepping pattern more effectively than BWSTT by correcting for inconsistencies in facilitation and increasing training time by lessening the physical requirements placed on trainers. In a multicenter 2-year investigation, the effects of DGO training on overground walking were studied in 20 persons with incomplete SCI. At the completion of the project, significant improvements in walking velocity and endurance were observed, causing researchers to conclude that DGO training was a promising therapy which improved overground walking ability in persons with incomplete SCI while reducing physical and personnel demands (Wirz et al., 2005). However, no changes were demonstrated in the use of assistive ambulation devices or the need for physical assistance (Wirz et al.).

While evidence shows that DGO training can be beneficial, challenges to implementing this therapeutic approach also exist. In a study quantifying the metabolic costs of body weight supported walking and walking using a DGO, it was found that the metabolic cost of DGO walking was lower than that measured while walking with body weight support. It has been hypothesized that the pelvic stability and guidance provided by the DGO device during the swing phase of gait may account for the lower energy demands associated with DGO walking (Israel et al., 2006). However, if the goal of gait training is to increase walking capability in normal living environments, the imposition of realistic metabolic challenges must be part of the overall training demand. Additional criticisms of DGO walking include the generation of abnormal patterns of muscle activation and intensity and inappropriate sensory cuing attributed to a fixed ankle position, resulting in greater stretch placed on the knee flexors during imposed knee extension (Israel et al.). Viewed collectively, these limitations suggest that DGO training may reduce maximal recovery by patients (Israel et al.).

Underwater treadmill training. Observations of individuals walking in water suggest that the level of body weight support provided by water buoyancy leads to a more comfortable and normal unloading for deconditioned persons than that created by a harnessing system featuring point-specific unloading (Giaquinto et al., 2007). Water walking allows for normal variation in gait patterns to occur, enabling participants to express individual features of their own walking style. Without the pelvic stability provided by a harnessing system, participants who walk in an aquatic setting are able to experience greater excursions of weight shift and take advantage of longer reaction times to correct inappropriate alterations in balance, leading to improvements in core stability and balance. The aquatic environment also maximizes afferent feedback from all directions, which may increase the stimulation of cutaneous receptors and influence step cycle activity (McCrea, 2001).

In recent years, there has been greater interest in the use of UTT as a potential means of realizing the benefits of water walking in a controlled setting. With UTT, clinicians and researchers can easily and efficiently manipulate and reproduce gait speed, water depth, and water temperature, all of which can influence metabolic response to exercise (Byrne et al., 1996). Other advantages of underwater treadmill exercise include the similarity of muscle activity and gait patterns used in land walking, minimization of postural distortions that often characterize forward walking in water, increased leg strength gained by overcoming water resistance and turbulence, enhanced range of motion, and decreased pain (Bryne et al.; Napoletan, 1994). While the impact of underwater treadmill training has not been documented in the SCI population, anecdotal information suggests that it may be a beneficial clinical intervention that addresses a number of limitations encountered when using alternative weight-unloading systems (Groopman, 2003).

Overall Summary

Published research supports the concept that participation in physical activities and restoration of walking leads to improved health and quality of life among individuals with SCI. In order to better understand how to improve gait function after SCI, relationships among variables hypothesized to influence community ambulation in the SCI population should be examined to aid clinicians in helping persons with SCI reach benchmark levels of ambulatory speed and leg strength needed to sustain meaningful levels of community walking. While a handful of therapies exist to enhance walking ability in persons with SCI, limitations and drawbacks in their application suggest the need to explore new methods of gait rehabilitation in this population. In this regard, a promising rehabilitative approach is underwater treadmill training, which features uniform unloading, increased sensory feedback, the ability to establish and reproduce key training parameters, and the freedom to explore individual characteristics of gait in an environment that provides challenging, yet acceptable, levels of resistance to facilitate the development of balance and lower-extremity muscle strength. In addition, underwater treadmill training provides a safe and enjoyable environment for training and has the potential to be implemented in community settings, thereby increasing accessibility.

As a final point, one of the most encouraging outcomes presented in this review is the recognition that neuronal networks in the spinal cord can be modified by use in functional activities. The adaptive capacity of the central nervous system may prove to be an essential component of any strategy designed to restore walking following SCI. To accomplish this goal, future walking interventions may need to combine multiple approaches and interdisciplinary collaborations to maximize recovery in persons with neurological injuries.