Spinal Cord (2014) 52, 287–291

www.nature.com/sc

ORIGINAL ARTICLE

# Reliability and relatedness of peak $VO_2$ assessments during body weight supported treadmill training and arm cycle ergometry in individuals with chronic motor incomplete spinal cord injury

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**Study design:** Prospective assessment as part of initial evaluations for randomized-controlled trial participation.

**Objectives:** To determine the test–retest reliability of peak $VO_2$ testing during both robotically assisted body weight supported treadmill training (RABWSTT) and arm cycle ergometry and to assess whether a relationship exists between these two measurements in individuals with chronic motor incomplete spinal cord injury (CMISCI).

**Methods:** Twenty-one participants with CMISCI enrolled in a 3- month, RABWSTT randomized-controlled trial. As part of their baseline assessments, individuals underwent $VO_2$ peak assessments twice on separate days during both RABWSTT and arm cycle ergometry using a metabolic cart.

**Results:** Peak oxygen consumption measured at baseline correlated significantly between repeated tests in the RABWSTT ($r=0.96$, $P<0.01$) and the arm ergometer ($r=0.95$, $P<0.01$). A Pearson correlation ($r=0.87$, $P<0.01$) existed between the peak $VO_2$ measurements obtained using RABWSTT and arm ergometry, although Bland–Altman analysis suggested a more limited relationship with a bias of 1.1 favoring arm ergometry. This relationship was stronger for individuals with tetraplegia than for people with paraplegia.

**Conclusion/clinical relevance:** Determination of $VO_2$ peak during both RABWSTT and arm ergometry in individuals with CMISCI is highly reproducible. Furthermore, a moderate correlation exists between peak $VO_2$ measured during RABWSTT and arm cycle ergometry in this population for individuals with tetraplegia. This correlation offers implications for future cardiovascular testing of individuals with CMISCI, as two reliable peak $VO_2$ measurement techniques are possible.

*Spinal Cord* (2014) **52,** 287–291; doi:10.1038/sc.2014.6; published online 18 February 2014

**Keywords:** robotically assisted body weight supported treadmill training; chronic motor incomplete spinal cord injury; peak $VO_2$; reproducibility; validity

## INTRODUCTION

Individuals with spinal cord injury (SCI) experience decreased lean muscle mass and increased total body and abdominal fat, predisposing them to a higher incidence of diabetes, hypertension and dyslipidemia than able-bodied people.[1–4] These problems, in part, are caused by neuromuscular limitations following injury and the subsequent associated sedentary lifestyle. Physical activity is recommended to combat these health-related problems. Unfortunately, the person with SCI holds limited activity options. Several evidence-based guidelines exist for the able-bodied population, including the Adult Treatment Panel III, which recommends aerobic exercise to achieve cholesterol modification and weight reduction.[5] However, specific available exercise guidelines are limited for individuals with SCI, and the associated restricted muscle activation, secondary metabolic derangements and barriers to accessing exercise opportunities may limit activity engagement.[6–8] This lack of optimal aerobic exercise recommendation for individuals with SCI partially stems from limited information about exercise peak $VO_2$ responses, a primary dependent variable for determining adequate aerobic training. These cardiovascular measures are difficult to reliably assess on the 'gold-standard' treadmill because muscle weakness, gait disturbances and/or use of assistive devices all may interfere with peak $VO_2$ assessment. Measurement of peak $VO_2$ assessed via arm cycle ergometry for individuals with CMISCI is currently utilized,[9–11] but the relationship between upper and lower extremity exercise is not previously reported.

Various robotic treadmill training devices provide lower extremity movement assistance for individuals with gait deficits. One device, the Lokomat, an exoskeletal robotically assisted, body weight supported treadmill training (RABWSTT) device (Hocoma AG, Zurich, Switzerland), is included in treatment and exercise programs for individuals with MISCI.[12] The impact of Lokomat training upon the cardiovascular system of individuals with MISCI is limited[13] with little information available addressing if peak $VO_2$ response can be effectively and reliably obtained during robotic assisted exercise. The relationship between peak $VO_2$ measurements during robotic treadmill

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Received 13 June 2013; revised 11 December 2013; accepted 13 January 2014; published online 18 February 2014

training and arm cycle ergometry is unknown. This information would be useful to better understand the impact of exercise interventions upon the cardiovascular fitness of individuals with MISCI.

This paper reports the test–retest reliability of both RABWSTT and arm cycle ergometer devices while eliciting peak $VO_2$ response in individuals with chronic motor incomplete spinal cord injury (CMISCI). In addition, for the same population, we assess whether a relationship exists between RABWSTT and arm cycle ergometry facilitated peak $VO_2$. Although the quantity measured is the same under both testing paradigms, there has been no previous data defining the relationship, especially in the CMISCI population with highly variable upper and lower extremity motoric capabilities. Establishing such a relationship if it exists would be useful, for example, in cases where assessment of cardiovascular training impact is desired in an individual who is unable to complete peak $VO_2$ arm cycle ergometry testing due to excessive upper extremity tone.

## MATERIALS AND METHODS

### Participants

Participants were selected based on established clinical safety guidelines from the outpatient SCI clinics at an academically affiliated 132 bed rehabilitation hospital center and an academically affiliated outpatient Department of Veterans Affairs SCI support team clinic within the same city. Eligible participants sustained a SCI at least 12 months before enrollment, were between 18 and 80 years old, with a confirmed level of injury between C4 and L2, and AIS of either C or D. Study participants were required to tolerate 30 vertical minutes in a standing frame, but community ambulation was not a requirement. Individuals were excluded with a history of uncontrolled hypertension, unstable angina, congestive heart failure, chronic obstructive pulmonary disease, symptomatic peripheral arterial occlusive disease or recent (within the last 3 months) hospitalization for any medical problem. Individuals with severe contractures or frequent uncontrolled bouts of autonomic dysreflexia were also ineligible.

Thirty-five individuals were screened under this protocol. Eight individuals failed screening. Three were found to be ASIA impairment scale B, two had bone mineral densities below the IRB established criteria ( $-3.5$ below s.d. see below), one had severe pulmonary disease, one had an abnormal EKG and one individual failed to complete the screening process. Six people withdrew from the study: three due to compliance issues, two with psychosocial issues and one individual demonstrated symptomatic hypotension while in the Lokomat. Therefore, 21 individuals with chronic ($>$one year post injury) motor incomplete SCI (19 males and 2 females) with ASIA Impairment Scale (AIS) C (2) or D (19) between the ages of 25 and 72 (average $= 51.1 \pm 13.7$ years) were ultimately selected and agreed to participate in a 3-month training, randomized-controlled trial to determine the RABWSTT effectiveness on gait function and aerobic capacity (Table 1).

**Table 1 Demographics of the 21 participants**

| | *Mean* | *Range* |
|---|---|---|
| Age (years) | $51.1 \pm 13.7$ s.d. | 25–72 |
| Time since injury (months) | $129 \pm 150$ | 12–400 |
| Mass (kilograms) | $83.3 \pm 19.8$ s.d. | 45.8–129.8 |
| Body fat (percent) | $33.7 \pm 7.6$ s.d. | 22.2–44.6 |
| Gender | 19 males | 2 females |
| *Level and extent of injury* | | |
| Cervical: C1-C4 | | 9 |
| Cervical C5-C8 | | 6 |
| Thoracic T1-T12 | | 5 |
| Lumbar | | 1 |
| AIS Classification C | | 2 |
| AIS Classification D | | 19 |
| LEMS Range | | 14–49 |

Abbreviations: AIS, ASIA impairment scale; LEMS, lower extremity motor score.
Demographic information on the individuals with spinal cord injury in this research protocol.

### Methods

Baseline evaluations included a full history and physical examination, electrocardiogram, Dual Energy X-ray Absorptiometry (DXA) testing and serum laboratory tests to screen for renal disease, liver disease and uncontrolled diabetes. Neurologic assessments were completed using the International Standards for Neurological Classification of Spinal Cord Injury. The DXA studies were performed using a GE (Lunar) Prodigy, and were done primarily to determine whole-body bone mineral density values, as for safety reasons we excluded individuals with values less than 3.5 s.d. below the age-matched normal value. This exclusion criterion was established in consultation with our local IRB in order to avoid the risk of fracture during Lokomat exercise.

### Lokomat Testing

All participants completed two to three 20-min acclimation training sessions in the Lokomat before the measurement of peak aerobic capacity in the device with sessions designed to expose participants to the body weight support (BWS) system (0–100%) and treadmill speed (1.6–3.2 kilometers per hour (kph)).

Participants performed a 3- min warm-up phase in the Lokomat at the start of the peak $VO_2$ test with the initial work rate settings at 1.5–1.8 kph for treadmill speed with robotic BWS maintained at 100%. Next, the exercise phase was initiated to induce a peak $VO_2$ response by periodically modifying work rates (speed and BWS) every 2–3 min. Treadmill speed was increased by 0.2–0.3 kph during these adjustment intervals. Using visual gait assessment, the physical therapist reduced BWS during these adjustment intervals ideally minimizing BWS while maintaining the desired gait pattern. Participants were instructed to actively assist the robot through the gait cycle to generate a cardiac ‘workout’, and the RABWSTT LCD screen provided visual feedback of participant effort. Termination of each test (9–15 min) occurred with volitional fatigue or if the participant was unable to perform the required work rate with an appropriately aligned gait pattern.

### Arm cycle ergometry testing

Participants performed two peak $VO_2$ arm cycle ergometer tests using a standard desktop mounted device (Figure 1b) with a 3- to 5-min warm-up at zero resistance using a self-selected pedal cadence. The exercise phase followed this warm-up period with the work rate adjusted every minute by increasing the resistance to the flywheel, and instruction given to maintain a self-selected rotational cadence at each new work rate. Termination of each peak test occurred at volitional fatigue or if participants could not maintain the self-selected pedal cadence. If needed, hand stability positioning straps were utilized during arm cycle ergometry.

An exercise physiologist administered all arm cycle and RABWSTT protocols including a graded exercise paradigm with periodic work rate increases until volitional fatigue occurs.

### Determination of peak $VO_2$ values

For both the Lokomat and arm cycle ergometer tests, air flow and gas exchange data was continuously monitored with the VMAX Encore Metabolic Cart (Sensormedics, a subsidiary of VIASYS Healthcare, Yorba Linda, California), an open circuit spirometry device used to determine oxygen consumption ($VO_2$) and carbon dioxide production ($VCO_2$). To collect the gases, participants donned a Hans Rudolph mask, which interfaced to the metabolic cart through a flow meter and sample lines. Figures 1a and b illustrate this set-up procedure in both test modalities (RABWSTT and arm cycle ergometry). A computer software program integrated the data to provide $VO_2$, $VCO_2$, pulmonary ventilation (VE) and respiratory exchange ratio (RER) (expired $VCO_2/VO_2$ consumed) every 20 s. Our $VO_2$ peak value was the average of the two highest consecutive 20-s sampling points.

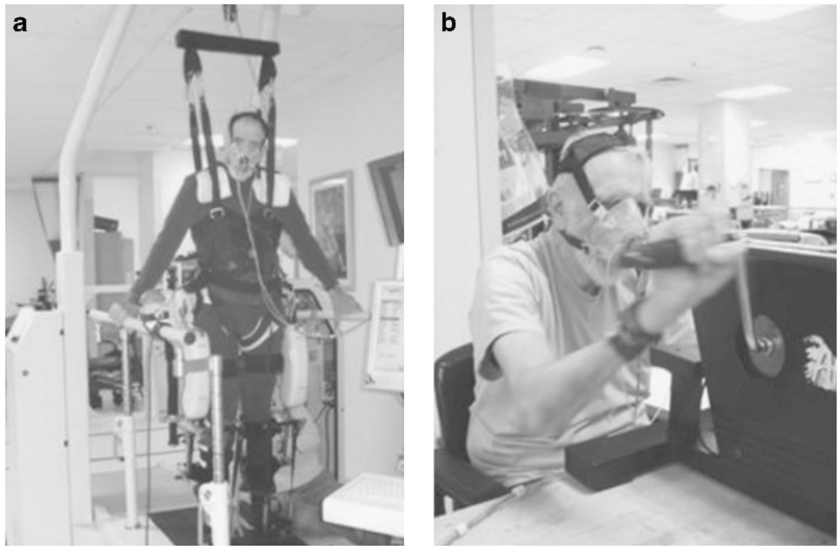


**Figure 1** (**a**, **b**) Two pictures illustrating the exercise modalities (Robotic assisted body weight supported treadmill training (RABWSTT) and arm cycle ergometry) and the method implemented in the collection and determination of peak oxygen consumption ($VO_2$ peak).

### Statistical analyses

Determination of the test–retest reliability of both the arm cycle ergometer and RABWSTT to induce peak $VO_2$; and the RABWSTT $VO_2$ and arm cycle ergometer $VO_2$ relationship occurred. Individual person data were normalized to body weight in kilograms for each subject. A correlation coefficient indicated the reliability of the repeated measures for the $VO_2$ measurements on each device separately. High reliability was defined as an *r*-value greater than 0.85.[14] Assessment was also completed between the two $VO_2$ peak measurements devices (Lokomat and arm ergometer) to examine any existing relationship. This relationship was evaluated with both the Pearson correlation coefficient and the Bland–Altman statistic,[15] in which the differences between the two $VO_2$ measurements were plotted against the means for each subject.

### Statement of ethics

The University of Maryland Baltimore Institutional Review Board, the Baltimore VA Medical Center (VAMC) Research Committee, and the Kernan Hospital Medical Executive Committee approved this protocol. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during this research.

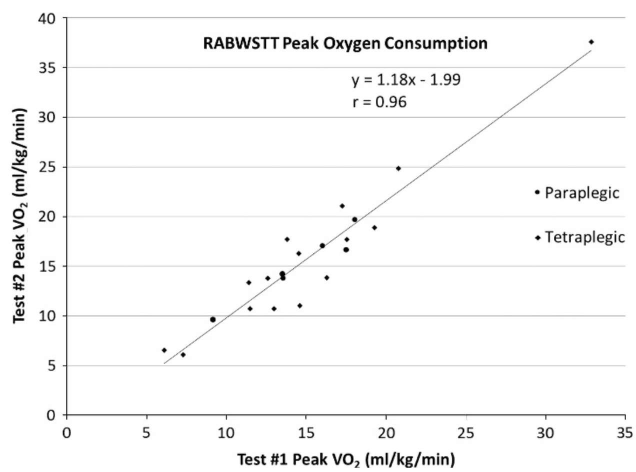


**Figure 2** Test–retest reliability of peak oxygen uptake ($VO_2$ peak) obtained during robotic-assisted body weight supported treadmill training (RABWSTT). Each data point represents an individual participant. Diamonds represent tetraplegic individuals and circles represent paraplegic individuals.

## RESULTS

Twenty-one participants tolerated two sessions each of RABWSTT and arm cycle ergometry testing. There were 15 individuals with tetraplegia based on total ISNCSCI assessment with nine of them at C4 or above and six at C5 to C8. Six individuals displayed paraplegia, five from T1 to T12 and one at L2. The participants displayed an average body mass of 83.3 kg ($\pm$19.8 s.d., range 45.8–129.8) and average body fat of 33.7 percent ($\pm$7.6 s.d., range 22.2–44.6). Individuals varied widely in their peak $VO_2$ measurements. For the RABWSTT paradigm, peak $VO_2$ measurements ranged from 6.1 to 37.6 $ml^{-1} kg^{-1} min^{-1}$ with an average of value $15.1 \pm 5.5$ for test 1 and $15.8 \pm 6.8$ for test 2. The results for the arm cycle ergometry paradigm ranged from 9.3 to 36.5 $ml^{-1} kg^{-1} min^{-1}$ with an average of $16.3 \pm 6.4$ for test 1 and $16.7 \pm 4.9$ for test 2. Peak oxygen consumption measured at baseline correlated significantly between repeated tests in the RABWSTT ($r = 0.96$, $P < 0.01$) (Figure 2) and the arm cycle ergometer ($r = 0.95$, $P < 0.01$) (Figure 3). Significant positive correlation ($r = 0.87$, $P < 0.01$) also occurred for the comparison of average (test 1 and test 2) peak $VO_2$ measurements obtained using RABWSTT and arm cycle ergometry (Figure 4).

To insure a more thorough assessment of the relationship between the peak $VO_2$ measurements using the two different techniques (RABWSTT and arm cycle ergometry), Bland–Altman plots were utilized. These plots were constructed for all data ($n = 21$) as well as for the tetraplegic data only ($n = 15$) (Figures 5a and b). For the entire data set, the mean difference, or bias in the two methods of $VO_2$ determination was 1.1 with the measurement using the arm cycle ergometer greater than that obtained using RABWSST. Two s.d. put the estimated range of mean differences as $-4.9$ to 7.1 $ml^{-1} kg^{-1} min^{-1}$, with all but one subject falling within this range or limit of agreement. When the tetraplegic data were assessed alone, the relationship was closer, with a mean difference favoring the arm cycle ergometer of only 0.5 and a narrower estimated range of mean differences of $-4.4$ to 5.3 $ml^{-1} kg^{-1} min^{-1}$, and no points outside

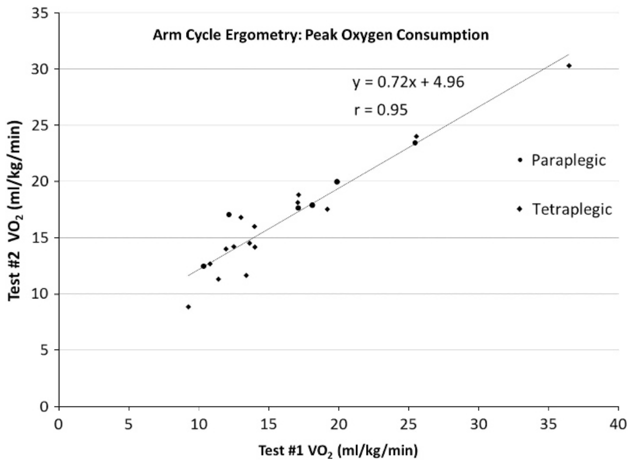


**Figure 3** Test–retest reliability of peak oxygen uptake ($VO_2$ peak) obtained during arm cycle ergometry. Each data point represents an individual subject. Diamonds represent individuals with tetraplegia and circles represent individuals with paraplegia.

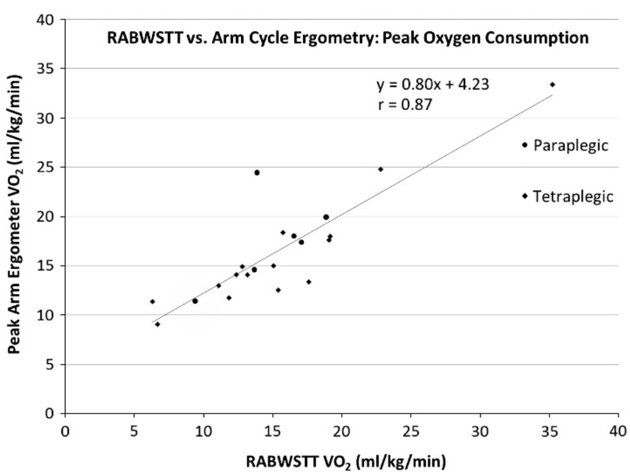


**Figure 4** Correlation between peak oxygen uptake ($VO_2$ peak) obtained during RABWSTT and arm cycle ergometry. Values of the *x* and *y* coordinates for each subject represent the averages of the two trials for each testing modality.

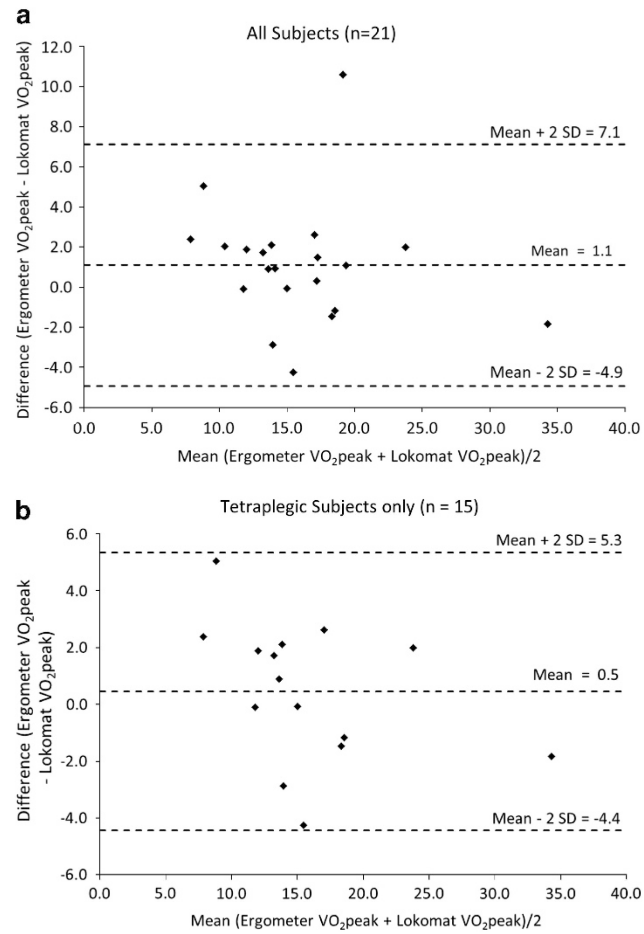


**Figure 5** Bland–Altman plots of $VO_2$ peak data for all subjects (**a**) and for the tetraplegic individuals only (**b**). Differences between the two methods are graphed against the means of the two methods. Means and ±2 s.d. lines are drawn. Bias is smaller and s.d. lines are tighter when the tetraplegic individuals are evaluated alone.

the two s.d. range. The mean difference for the small ($n=6$) paraplegic group alone was calculated at 2.7, meaning that on average the $VO_2$ peak was $2.7\,ml^{-1}\,kg^{-1}\,min^{-1}$ greater in the paraplegic individuals when doing arm cycle exercise than Lokomat exercise.

## DISCUSSION

We are among the first research groups to investigate the test–retest reliability of peak oxygen consumption measurement using the RABWSTT and arm cycle ergometry, and to evaluate the relationship between RABWSTT and arm cycle ergometry peak $VO_2$ measurements for individuals with CMISCI. Investigation into test–retest reliability of arm cycle ergometry peak $VO_2$ is important to understand as currently it is not a standardized cardiovascular assessment tool for individuals with CMISCI. It is however used clinically in cardiac stress testing protocols for people with lower extremity paralysis in situations where pharmacologic (thallium) stress testing is not desirable. Those with incomplete paralysis, who are unable to undergo standard treadmill exercise testing, are able to train and test their cardiovascular system with RABWSTT. As RABWSTT conditions are increasingly used for fitness training in individuals with CMISCI, it is important to understand the reproducibility and relatedness of this technique to the arm cycle ergometry standard. In this population, the neurologic impairment often includes autonomic impairment, offering altered heart rate and blood flow responses that could potentially dissociate the cardiovascular effects of upper body exercise from those of lower body exercise. It is therefore important to understand this relationship between arm cycle ergometry and RABWSTT as we employ varied interventions to improve cardiovascular fitness for individuals with CMISCI.

### Arm cycle ergometry testing

Bulthuis *et al.*[16] reported the arm crank is a reliable tool to measure $VO_2$ peak during exercise as well as submaximal $VO_2$ in able-bodied subjects. Using a 6-minute arm cycle testing paradigm, Hol *et al.*[11] stated a similar result for a cohort of individuals with SCI with mean $VO_2$ peak $18.6\pm8.4\ ml^{-1}\,kg^{-1}\,min^{-1}$, similar to our results. Hol *et al.*[11] concentrated on a measure of $VO_2$ at submaximal effort based on a desire to maintain constant power output during the 6 minutes. This was not our emphasis, we aimed to understand the peak measurement, which is considered the criterion standard of cardiovascular fitness during treadmill exercise testing. Submaximal steady state exercise would be difficult to standardize using RABWSTT, given the anticipated injury variability encountered in this population.

### Upright RABWSTT testing

Researchers examining the cardiovascular (CV) fitness parameters including $VO_2$ peak of individuals post stroke report strong test–retest reliability utilizing treadmill exercise assessments.[17,18] However, an important difference exists between individuals post stroke and post CMISCI related to CV fitness testing with the standard treadmill testing protocol. For people with CMISCI especially those who are nonambulatory in the community, CV fitness assessment on a treadmill may not be possible without robotic assistance. In addition, altered autonomic responses to upright exercise might hamper results, although in this cohort, there were no major autonomic problems (either with hypotension or dysreflexia) during exercise. Passive robotic gait training without some voluntary effort would be insufficient to increase cardiopulmonary fitness in people with SCI. In a case report, researchers demonstrated that body weight supported treadmill training needed active exercise engagement to achieve the desired training intensity as monitored by $VO_2$.[13] Jack *et al.*[19] investigated the impact of body weight supported treadmill exercise upon the cardiopulmonary fitness of two men with CMISCI indicating an improvement in $VO_2$ peak. Consistent with our test–retest findings, this research group also reported a high reliability ($r = 0.95$), for peak $VO_2$ measured during RABWSTT in a study consisting of nine men with CMISCI.[20] They concluded that robotically assisted training could be an adequate stressor of the cardiovascular system when compared in a similar way with arm crank ergometry.

When evaluating the relationship between results using arm cycle ergometry and RABWSTT techniques, initial standard analysis using correlation techniques suggest a robust relationship. The Bland–Altman analysis, however, demonstrates a more limited relationship, indicating improvement in one peak $VO_2$ test may not produce a proportional improvement in the other peak $VO_2$ exercise testing condition. The relationship was stronger for individuals with tetraplegia than those with paraplegia. Perhaps this was due to the variability among the paraplegic individuals with essentially normal upper body capabilities, and consequently could work harder using arm cycle ergometry than using their paraparetic legs. Their surrogate measure of cardiovascular fitness was better achieved using an arm exercise testing condition. This also explains the stronger bias in the total group (1.1) and in the paraplegic group (2.7) compared with the tetraplegic group alone (0.5).

This work is limited by the small number of participants as well as the safety selectivity of the sample size. Nonetheless, only one screening failure was due to physiologic considerations despite the extensive pre-established exclusion criteria for safety reasons.

Our work supports the Lokomat, a RABWSTT robotic device, besides being an exercise device, can be employed as a reliable and valid tool to facilitate an appropriate aerobic work challenge when assessing peak oxygen consumption for individuals with CMISCI. In addition, the data provide early evidence of a relationship between measurement of $VO_2$ peak using upper extremity exercise and that using robotically assisted leg exercise in persons with CMISCI with this relationship stronger in individuals with tetraparesis than those with paraparesis. The data do not support substitution of one measurement technique for the other, as it is likely that slightly different aspects of cardiovascular fitness are measured under each testing condition in this CMISCI population with highly variable upper and lower extremity motoric capabilities.

## DATA ARCHIVING

There were no data to deposit.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

## ACKNOWLEDGEMENTS

This study was funded by a Department of Veterans Affairs Rehabilitation R&D Service Merit Review Award (B4027I). The following physical therapists expertly provided our study's intervention component: Naomi Price-Miller, Megan Eyvazzadeh, Jean McQuaid. Gertrude Morrison, RN and Deborah Miller, RN assisted in recruitment of study participants. We acknowledge the help of Richard Macko, MD and Fred Ivey, PhD in the initial design of the study.

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