Research Article

Verification testing to confirm VO_2max attainment in persons with spinal cord injury

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Context/Objective: Maximal oxygen uptake (VO_2max) is a widely used measure of cardiorespiratory fitness, aerobic function, and overall health risk. Although VO_2max has been measured for almost 100 yr, no standardized criteria exist to verify VO_2max attainment. Studies document that incidence of ‘true’ VO_2max obtained from incremental exercise (INC) can be confirmed using a subsequent verification test (VER). In this study, we examined efficacy of VER in persons with spinal cord injury (SCI).

Design: Repeated measures, within-subjects study.

Setting: University laboratory in San Diego, CA.

Participants: Ten individuals (age and injury duration = 33.3 ± 10.5 yr and 6.8 ± 6.2 yr) with SCI and 10 able-bodied (AB) individuals (age = 24.1 ± 7.4 yr).

Interventions: Peak oxygen uptake ($\text{VO}_{2\text{peak}}$) was determined during INC on an arm ergometer followed by VER at 105 percent of peak power output (% PPO).

Outcome Measures: Gas exchange data, heart rate (HR), and blood lactate concentration (BLA) were measured during exercise.

Results: Across all participants, $\text{VO}_{2\text{peak}}$ was highly related between protocols (ICC = 0.98) and the mean difference was equal to 0.08 ± 0.11 L/min. Compared to INC, $\text{VO}_{2\text{peak}}$ from VER was not different in SCI (1.30 ± 0.45 L/min vs. 1.31 ± 0.43 L/min) but higher in AB (1.63 ± 0.40 L/min vs. 1.76 ± 0.40 L/min).

Conclusion: Data show similar $\text{VO}_{2\text{peak}}$ between incremental and verification tests in SCI, suggesting that VER confirms VO_2max attainment. However, in AB participants completing arm ergometry, VER is essential to validate appearance of ‘true’ $\text{VO}_{2\text{peak}}$.

Keywords: VO_2max incidence, Paralysis, Arm ergometry, Oxygen uptake, Blood lactate concentration

Introduction

Maximal oxygen uptake (VO_2max), the integration of cardiopulmonary oxygen transport and muscle utilization of oxygen, is the “gold standard” measure of cardiorespiratory fitness and recently has been identified as the best measure of long-term morbidity and mortality in able-bodied populations.¹ One goal of physical activity regimes is to improve VO_2max , hence current Physical Activity guidelines espouse a minimum of 150 min/wk of moderate intensity continuous exercise training (MICT).² In addition, the specific intensity of MICT is critical considering that a higher volume and

intensity of MICT elicit greater increases in VO_2max than low-volume, lower intensity training.³

Despite the use of VO_2max testing in the field of Exercise Physiology to assess cardio-respiratory fitness for almost 100 years and documented efficacy of exercise training to enhance VO_2max , there are no standardized criteria to confirm VO_2max incidence.⁴ Current approaches to confirm VO_2max incidence including a levelling off or ‘plateau’ in VO_2 , maximal HR within 10 b/min of age-predicted maximum ($220 - \text{age}$), and respiratory exchange ratio (RER) > 1.10 ,⁴⁻⁶ yet these are flawed, as they do not differentiate between people who show a ‘true’ VO_2max and those who do not.⁴⁻⁶ This inability to accurately verify if VO_2max actually occurred is concerning when VO_2max is used to identify health risk or judge the efficacy of chronic physical activity regimes.

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Recently, use of a constant load test performed at an intensity below, equal to, or greater than that attained at VO₂max (the verification test (VER)) has been used to confirm VO₂max attainment in participants differing in age and fitness level.⁵⁻⁹ This test is typically performed 5 - 10 min after the initial incremental VO₂max test and yields estimates of VO₂max which do not differ from the incremental value, hence verifying VO₂max attainment. However, if VO₂max is shown to be greater with VER, an even higher work rate needs to be employed to confirm VO₂max attainment.¹⁰

One population with a VO₂max on the low end of the fitness spectrum includes persons with spinal cord injury (SCI). It is apparent that onset of SCI leads to marked physical disability which diminishes participation in physical activity,¹¹ leading to a low VO₂max value. Fortunately, completion of chronic exercise training using modalities including arm ergometry¹² and circuit training¹³ increases VO₂max and physical function and potentially reduces health risks in this population; however, scientists have yet to develop criteria to confirm VO₂max attainment in this population. For example, in these studies, no criteria were denoted to identify VO₂max or verify its incidence. In another study in SCI athletes,¹⁴ the VO₂ plateau occurred in only 40% of all graded exercise tests performed. This low incidence of the VO₂ plateau combined with a lack of established criteria to confirm VO₂peak attainment in SCI is problematic when VO₂max is measured to assess cardiorespiratory fitness, or when VO₂max testing is used to monitor adaptation to habitual physical activity. One study¹⁴ in men with SCI showed VO₂peak values which were not different between INC and VER, but it was performed in international level athletes and used wheelchair ergometry, which is quite expensive, impractical, and inaccessible to most persons with SCI. In contrast, arm ergometry is a popular and more accessible exercise modality for persons with SCI as well as able-bodied (AB) individuals with impaired lower extremity function. To our knowledge, no study has utilized verification testing to verify VO₂max attainment in persons with SCI during arm ergometry.

The aim of the present study was to test the efficacy of VER in persons with SCI and compare their responses to AB. Verification testing was recently advocated¹⁰ as the best approach to verify VO₂max attainment, especially in untrained individuals. Use of VER to confirm VO₂max attainment in AB is grounded in the concept that VO₂ will not increase with increasing power output, due to limitations in the delivery and utilization of oxygen.¹⁵ Previously, it was purported that

upper-body exercise (UBE) such as arm ergometry, as typically performed by persons with SCI, is not limited by oxygen delivery but local muscle fatigue due to the smaller exercising muscle mass.¹⁶ However, data from a recent study¹⁷ in which hemodynamic responses were examined during cycling as well as arm ergometry demonstrated that VO₂max is limited by O₂ delivery even for arm cranking exercise. Nevertheless, studies showing efficacy of VER obtained from whole-body exercise including cycling^{6,8} and running^{5,18} cannot necessarily be translated to small muscle mass exercise. It was hypothesized that in response to UBE in both populations, VER will elicit estimates of VO₂max which do not significantly differ from INC, as previously shown.^{6,8}

Methods

Participants

Habitually active men and women at least 12 months post-SCI (injury duration = 6.8 ± 6.2 years) were recruited from a local SCI rehabilitation facility as well as through word-of-mouth. They consisted of two tetraplegics and eight paraplegics who regularly completed wheeling, resistance training, locomotor training, surfing, stretching, and assisted/unassisted walking. Four had complete SCI; whereas, six had incomplete SCI. Participants were free of disease and musculoskeletal ailments including shoulder weakness or pain preventing them from completing the study. Inclusion criteria were injury lower than C2 and non-ventilator dependent, physician permission to engage in intense exercise, no medication use which may affect exercise tolerance, and ages 18 - 60 years. Participants initially completed a health-history questionnaire and physical activity survey¹⁹ to verify their eligibility. Able-bodied participants included four men and six women who were physically active yet lacked previous experience with arm ergometry. They were healthy and non-obese and did not have any upper-extremity issues preventing UBE. Physical characteristics of all participants are demonstrated in Table 1. Data show that compared to SCI, AB were younger ($P = 0.03$), yet no differences were shown in body mass index, physical activity, or peak power output (PPO).

Experimental design

Participants came to the lab well-rested and hydrated and completed a single exercise session, which was preceded by a 2 hour fast and abstention from exercise for 24 hours. Peak oxygen uptake (VO₂peak) was determined during progressive arm ergometry to exhaustion followed by VER. During each trial, gas exchange

Table 1 Participant physical characteristics (mean $\pm$ SD).

Parameter	SCI	Range	AB	Range	P value
Age (yr)	33.3 $\pm$ 10.5	25 - 57	24.1 $\pm$ 7.4*	21 - 45	0.03
Sex	9 M/1 W	NA	4 M/6 W	NA	NA
Body mass index (kg/m ²)	22.6 $\pm$ 3.1	19.0–22.9	24.1 $\pm$ 3.4	20.2–27.4	0.33
Physical activity (h/wk)	8.1 $\pm$ 4.4	3 - 18	5.4 $\pm$ 2.7	2.5 - 10	0.11
$\text{VO}_{2\text{peak}}$ (L/min)	1.30 $\pm$ 0.45	0.66–1.94	1.63 $\pm$ 0.41	1.15–2.50	0.10
PPO (W)	96.3 $\pm$ 35.0	32 - 146	108.9 $\pm$ 25.9	75 - 163	0.37

SCI = participants with spinal cord injury; AB = able-bodied participants. *P < 0.05 between groups at baseline; M, men; W, women; NA, non applicable; PPO, peak power output.

data, heart rate (HR), blood lactate concentration (BLa), and perceptual responses were measured. Participants provided their written informed consent prior to study participation, and the research protocol was approved by the University Institutional Review Board. Data from participants with SCI were acquired from June – October 2016; whereas, data from AB were obtained in June 2017.

Assessment of $\text{VO}_{2\text{peak}}$

Participants were dressed in exercise attire for the $\text{VO}_{2\text{peak}}$ assessment. After recording of height and body mass and 2 minutes of seated rest, BLa was measured from a fingertip blood sample (Nova Biomedical, Waltham, MA) using a sterile 23 gauge lancet (Owen Mumford Inc., Marietta, GA). Subsequently, a 5 minute warmup at 7 Watts was completed, and then all participants performed UBE on a wall-mounted ergometer (Lode Angio, Groningen, the Netherlands) at a self-selected cadence until volitional exhaustion, which was identified as cadence less than 30 rev/min. This cadence was chosen as at pedal rates lower than this, the ergometer no longer applies the resistance. For each participant, the height of the arm ergometer was modified to align with the shoulder joint. During exercise, power output was increased in a ramp-like manner by 3 W/min for tetraplegics and 13 W/min for paraplegics; whereas, for AB, power output was increased from 8–20 W/min depending upon each participant's size and sex, resulting in test duration from 6–10 minutes.²⁰ This test duration should not elicit fatigue prior to achievement of $\text{VO}_{2\text{max}}$ in motivated individuals.²¹ Pulmonary gas exchange data were obtained every 15 seconds using a metabolic cart (ParvoMedics True One, Sandy, UT) which was calibrated pre-exercise according to manufacturer specifications. Three minutes following this bout, peak BLa was determined. After a 10 minute active recovery at 7 Watts, participants cranked at 105% PPO until exhaustion. Strong verbal encouragement was provided during exercise.

From each trial, $\text{VO}_{2\text{peak}}$ was identified as the mean of the two highest VO_2 values during the last 45 seconds of exercise. Peak values of HR, ventilation (V_E), respiratory exchange ratio (RER), and carbon dioxide production (VCO_2) were identified using the same technique. To identify a plateau in VO_2 despite an increase in work, we developed individual change in VO_2 (ΔVO_2) values for each participant, which were obtained from the last two data points of INC using the expected O_2 cost of UBE at various ramp rates.²² This approach is superior to using a single ΔVO_2 value (e.g. 150 mL/min), which is affected by the specific work rate increment of exercise as well as participants' body mass.⁵ For example, for an AB male with mass equal to 68 kilograms completing INC at 13 W/min, the ΔVO_2 identifying a plateau in VO_2 at end-exercise is ≤ 0.24 L/min. Duration of INC and VER was also recorded. Preliminary testing in our lab showed that in five AB men and women who repeated testing between 3 and 10 d apart, absolute $\text{VO}_{2\text{peak}}$ was not different between INC (1.86 ± 0.36 L/min and 1.88 ± 0.42 L/min, $P = 0.83$, $\text{CV} = 4.7\%$) and VER (2.02 ± 0.37 L/min and 1.95 ± 0.37 L/min, $P = 0.25$, $\text{CV} = 4.9\%$) and highly related ($\text{ICC} = 0.96$ and 0.97).

Rating of perceived exertion (RPE) was also acquired pre-exercise and immediately at end of INC using the 1 - 10 category ratio scale (CR-10).²³ The meaning of this scale was communicated before exercise by instructing participants to report perceptions of exertion in terms of their breathing, heart rate, and level of fatigue. Participants were asked to respond to this scale in terms of how they felt at that moment.

Statistical analyses

Data are reported as mean $\pm$ standard deviation (SD) and were analyzed with SPSS version 20.0 (Chicago, IL). The Shapiro-Wilk test was used to determine if data were normally distributed. Two-way ANOVA with repeated measures was used to examine differences in peak variables as well as BLa and RPE. If a significant F ratio was obtained, Tukey's post hoc test was

used to identify differences between means. The Greenhouse-Geisser correction was used to account for the sphericity assumption of unequal variances across groups. Independent t-test was used to examine baseline differences between SCI and AB. Effect size was determined using Cohen's d. Intraclass correlation coefficient, standard error of the mean, and minimum difference were calculated for VO₂peak between INC and VER. Bland-Altman plots were used to examine agreement between VO₂peak determined from INC and VER. Our sample size is similar to that of recent studies demonstrating efficacy of VER in sedentary men and women⁶ and children.⁹ Statistical significance was equal to $P < 0.05$.

Results

Gas exchange data

Table 2 shows differences in all peak gas exchange and related variables in INC and VER. Results showed a significant main effect and interaction ($P = 0.01$) for relative and absolute VO₂peak. Post hoc analyses showed that in AB, VER-derived absolute and relative VO₂peak was significantly higher ($\sim 8\%$, $P = 0.001$ and 0.003 , $d = 0.37$ – 0.49) than INC, yet in SCI, these values were not different. Respiratory exchange ratio was lower ($P = 0.005$, $d = 0.84$ – 1.0) in VER versus INC in both groups of participants. Ventilation was higher in VER compared to INC ($P = 0.001$, $d = 0.40$ – 0.61), yet there was no protocol X group interaction ($P = 0.43$). Able-bodied participants showed higher V_E than SCI ($P = 0.014$, $d = 1.21$). There was no difference in HRpeak ($P = 0.72$) or VCO₂ ($P = 0.12$) between INC

and VER, and no protocol X group interaction ($P > 0.05$).

The VO₂ plateau occurred in 80% and 90% of AB and SCI participants, respectively. Table 3 demonstrates Δ VO₂ values for all subjects and denotes whether the VO₂ plateau was met. Mean Δ VO₂ at VO₂peak was equal to 0.17 ± 0.12 L/min in AB and 0.11 ± 0.07 L/min in SCI.

Comparing responses between INC and VER

Figures 1 and 2 show the difference in VO₂peak between protocols in both SCI and AB. Across all 20 participants, the ICC was equal to 0.98 between protocols and the mean difference in VO₂peak was equal to 0.08 ± 0.11 L/min. There was no association ($r = 0.11$, $P = 0.65$) between the difference in VO₂peak between protocols and INC-derived VO₂peak. The standard error of the mean and minimum difference were equal to 0.02 L/min and 0.04 L/min, respectively. In SCI, the mean difference in VO₂peak between protocols was equal to 0.02 L/min. Between INC and VER, eight participants showed small differences in VO₂peak (-0.06 L/min – 0.04 L/min), although two participants showed large increases in VO₂peak (0.11 and 0.12 L/min = 8%). In AB, five subjects exhibited small differences (0.02 – 0.06 L/min) in VO₂peak between protocols; whereas, the other five participants showed differences ranging from 0.08 to 0.38 L/min (mean difference = 0.23 L/min = 13%).

Table 3 Change in VO₂ at VO₂max and VO₂ plateau attainment in able-bodied persons and those with spinal cord injury completing incremental arm ergometry.

Participant	Δ VO ₂ (L/min)	VO ₂ Plateau attainment
AB		
F	0.10	Yes
M	0.22	Yes
F	0.44	No
F	0.10	Yes
M	0.13	Yes
F	0.10	Yes
F	0.11	Yes
F	0.10	Yes
M	0.07	Yes
M	0.34	No
SCI		
F	0.11	Yes
M	0.17	No
M	0.06	Yes
M	0.09	Yes
M	0.15	Yes
M	0.23	Yes
M	0.00	Yes
M	0.03	Yes
M	0.08	Yes
M	0.14	Yes

AB, able-bodied; SCI, spinal cord injury; F, female; M, male.

Table 2 Gas exchange data in response to incremental and verification testing (mean $\pm$ SD).

Parameter	SCI	AB
Incremental test		
VO ₂ peak (L/min)	1.30 ± 0.45	1.63 ± 0.40
VO ₂ peak (mL/kg/min)	17.4 ± 4.7	24.0 ± 4.7
VCO ₂ peak (L/min)	1.69 ± 0.41	1.99 ± 0.61
RER	1.29 ± 0.12	1.23 ± 0.12
V_E (L/min)	54.9 ± 17.5	76.0 ± 16.9
HRpeak (b/min)	160.6 ± 29.1	176.4 ± 17.8
Time (min)	7.9 ± 1.6	6.9 ± 1.3
Verification test		
VO ₂ peak (L/min)	1.31 ± 0.43	$1.76 \pm 0.40^*$
VO ₂ peak (mL/kg/min)	17.6 ± 4.5	$26.0 \pm 4.3^*$
VCO ₂ peak (L/min)	1.69 ± 0.41	1.98 ± 0.62
RER	1.21 ± 0.10	$1.12 \pm 0.11^*$
V_E (L/min)	$62.3 \pm 21.4^*$	$86.8 \pm 20.9^*$
HRpeak (b/min)	160.2 ± 26.4	178.1 ± 12.8
Time (min)	$1.8 \pm 0.3^*$	$1.7 \pm 0.4^*$

SCI = participants with spinal cord injury; AB = able-bodied participants; * $P < 0.05$ versus incremental test within group.

Figure 1 VO_2peak attained on the incremental (x-axis) and verification (y-axis) test in all 20 participants. Open circles (○) equal AB and dark circles (●) equal participants with SCI. The line represents the line of identity ($y = x$).

Changes in BLA and RPE

During INC, blood lactate concentration increased ($P < 0.001$) from baseline in both SCI (1.52 ± 0.60 mM to 7.43 ± 2.80 mM) and AB (1.56 ± 0.47 mM to 8.49 ± 2.87 mM), yet there was no time X group interaction ($P = 0.44$). A similar pattern was seen for RPE, which increased during exercise ($P < 0.001$) and peaked at values equal to 8.8 ± 0.3 and 8.9 ± 0.3 in SCI and

AB, respectively, with no difference between groups ($P = 0.91$).

Discussion

This study tested the utility of verification testing to verify VO_2max attainment in individuals with SCI and AB participants of similar body mass index and physical activity. Data show that VO_2peak was not different between INC and VER in SCI, which would suggest that this bout is useful to verify VO_2max attainment in this population. However, AB demonstrated higher VO_2peak in response to VER, which suggests that standard INC using UBE may not elicit VO_2max in this population.

Previous studies^{24–25} examining VO_2max responses to various exercise protocols in SCI made no attempt to verify VO_2max attainment using any criteria. Moreover, a plateau in VO_2 infrequently occurs in response to UBE in SCI.²⁶ Together, this would suggest that much remains to be determined whether people with SCI can attain a ‘true’ VO_2max . In the present study, we used VER to confirm incidence of VO_2max obtained from graded arm ergometry due to limitations in primary (VO_2 plateau) or secondary criteria. Although the VO_2 plateau criterion has been used for several decades, its incidence widely varies across studies^{27–29} due to methodological differences including participant characteristics as well as alterations in the specific sampling interval^{28,30} and work rate increment³¹ used during graded exercise. Although, its frequency was high in our participants during INC (Table 3), which may be due to use of a 15 s sampling interval and application of an individualized work rate increment. In addition, various RERmax criteria (> 1.10 , 1.15 , etc.) exist to confirm VO_2max attainment, and 18 of 20 participants in the present study surpassed these threshold values. Moreover, peak BLA values surpassing 8 mM³² seem to represent a maximal effort, although this value is derived from AB participants performing large muscle mass exercise. In AB men, Poole *et al.*⁴ demonstrated that higher values of RER (> 1.10 or 1.15) occurred at submaximal intensities and in addition, that most participants did not achieve this BLA criterion, which led them to recommend that neither criterion be used to confirm VO_2max attainment. Although peak HR during UBE can approach values seen during whole-body exercise,³³ the values reported in AB (Table 2) are not within 10 b/min of age-predicted HRpeak equal to $220 - \text{age}$. In addition, many participants with SCI have altered sympathetic activity which blunts the HR response to exercise, leaving the

Figure 2 Bland-Altman plot for VO_2peak from both protocols. Open circles (○) equal AB and dark circles (●) equal participants with SCI. Solid line equals mean difference between verification and incremental VO_2peak ; dashed line equals mean $\pm 1.96 \times \text{SD}$.

HRpeak criterion as relatively impractical in this population. Although these criteria are widely used, they are not adequate to verify VO_2max attainment in SCI, and since none was specifically developed for this population as is recommended,⁵ it is cautioned to apply them to incremental UBE.

Our data showing no difference in $\text{VO}_{2\text{peak}}$ between INC and VER in individuals with SCI support previous results. In one study,¹³ wheelchair athletes including tetraplegics and paraplegics completed INC and VER on two separate days. In contrast to our study, they used wheelchair ergometry as the exercise mode rather than UBE, and VER consisted of a relatively greater power output (0.3–0.6% higher gradient) than that attained at the end of INC rather than a 5% greater power output as used in the current study. They reported no difference in $\text{VO}_{2\text{peak}}$ across both protocols and high reliability for these measures across days. In addition, they stated that a 6% difference in $\text{VO}_{2\text{peak}}$ between protocols is acceptable, which is what 80% of our SCI participants exhibited.

Nevertheless, in AB, mean $\text{VO}_{2\text{peak}}$ obtained from VER was higher than INC, and five AB participants showed higher $\text{VO}_{2\text{peak}}$ (~ 13%) in VER versus INC, which can be explained by the following factors. First, it is possible that INC served to familiarize some subjects with intense UBE, during which they may have terminated exercise prematurely due to local muscle discomfort and fatigue due to the small muscle mass engaged. They then used this experience to exercise maximally during VER and attain a higher $\text{VO}_{2\text{peak}}$. Although data from all participants showed no relationship between baseline $\text{VO}_{2\text{peak}}$ and the difference in VO_2 between protocols, the three AB participants with the lowest $\text{VO}_{2\text{peak}}$ equal to 20 mL/kg/min showed substantial differences in VO_2 between protocols, which suggests that baseline fitness in AB may modify the magnitude of difference in $\text{VO}_{2\text{peak}}$ between INC and VER. Second, excessive bodily movement due to torso stabilization may augment VO_2 during UBE.¹⁶ We noted that many participants attempted to engage their hips and trunk to tolerate the supramaximal power requirement of VER, which may have led to elevated VO_2 . This additional torso movement may be lower in individuals with SCI, partially explaining why $\text{VO}_{2\text{peak}}$ did not differ between INC and VER. Third, fatigue of higher threshold fast twitch motor units recruited during supramaximal exercise³⁴ as well as removal and oxidation of BLa³⁵ in response to INC may enhance VO_2 contributing to the greater $\text{VO}_{2\text{peak}}$ observed in this protocol. When VER leads to higher estimates of $\text{VO}_{2\text{peak}}$ versus INC, we recommend that

an additional VER bout be performed at a higher intensity until VO_2 does not continue to increase.

Previous results⁷ suggest that a 2 min VER duration is adequate to elicit VO_2max . Similarly, data⁸ in men and women (VO_2max = 50 mL/kg/min) demonstrate a VER duration equal to 2.0–2.7 min in response to running at 115% of the velocity at VO_2max . In obese adults performing VER at 100%PPO, Sawyer *et al.*³⁶ reported VER duration equal to 1.9 min, and their data showed no difference in VO_2max between INC and VER. In another study, constant load supramaximal exercise as brief as 1.25 minutes elicited VO_2max in young men.³⁷ Our data showed VER duration < 2 minutes which was not different across groups (Table 2), and there was similar discrepancy in VER duration in AB (1.2–2.3 minutes) and SCI (1.1–2.1 minutes). In addition, no relationship was seen between this duration and INC ($P = 0.09$) or VER-derived $\text{VO}_{2\text{peak}}$ ($P = 0.21$), PPO ($P = 0.19$), BMI ($P = 0.61$), or the difference in $\text{VO}_{2\text{peak}}$ between protocols ($P = 0.20$), which suggests that the absolute increase in VO_2 during INC does not seem to modify time to exhaustion during VER. We encourage other scientists to conduct further studies manipulating the intensity of VER, especially in persons with SCI, to identify optimal protocol characteristics to confirm VO_2max attainment in this population.

Although our participants had similar BMI, PPO, and physical activity, relative $\text{VO}_{2\text{peak}}$ was higher in AB compared to SCI. Whether a greater fitness level modifies efficacy of VER to confirm VO_2max attainment is unlikely, considering that VO_2max values are not different between INC and VER in runners,⁵ active men and women,^{38–39} sedentary men and women,⁶ paraplegics and tetraplegics,¹³ and older adults.⁴⁰ The disparity of men and women differed across the two groups, although any effect of this discrepancy on our outcomes is likely small as no data show a unique effect of sex on VO_2max estimates from VER. During exercise, cadence was not standardized across participants, which may be a limitation considering that cadence equal to 70 rev/min in AB elicits higher VO_2max compared to lower cadences (30 and 50 rev/min).³³ Nevertheless, the ergometer used applies work rate independent of cadence, all participants typically maintained cadence above 60 rev/min during INC, and a common strategy during VER was to increase cadence above 80 rev/min upon application of the supramaximal workload. Unlike another study,⁴¹ we only used a single supramaximal intensity in VER equal to 105%PPO, so we cannot say for certain that this work rate is optimal for eliciting ‘true’ VO_2max

during UBE. In fact, submaximal constant load exercise at 90%PPO elicits VO₂max in AB,^{7,29} and this intensity which is above critical power may be superior to verify incidence of VO₂max during UBE, especially in persons with low fitness such as SCI.

Conclusion

Persons with SCI exhibit significantly higher rates of obesity, diabetes, and heart disease than able-bodied individuals⁴² which is partially attributed to their high level of inactivity and low VO₂peak. Testing of VO₂peak is performed in this population to establish aerobic fitness and monitor adaptations to exercise training. Nevertheless, no standardized methods exist to confirm VO₂max attainment in SCI. Our results show that verification testing elicits VO₂max values which are not different compared to incremental exercise when conducted properly, thus may be effective to establish 'true' VO₂max.

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Conflict of interest The authors declare that they have no conflict of interest in the completion of this study.

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