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Physiological responses in males with and without spinal cord injury to recumbent synchronous versus seated asynchronous arm crank stress tests

Respuestas fisiológicas en hombres con y sin lesión medular al realizar pruebas de esfuerzo con ergómetros de brazos sincrónico en posición horizontal y asincrónico en sedestación

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Abstract. Introduction: Maximal oxygen uptake (VO_2) may be one of the most important variables in the study of the responses of people with spinal cord injury (SCI) and without SCI to physical exercise. The results achieved during its assessment serve as a diagnostic and health indicator in clinical settings. Objective: this study aimed to investigate the physiological responses in males with and without SCI performing a maximal incremental test on an asynchronous arm crank ergometer (ACr) and on a recumbent synchronous handbike ergometer (HB). Methods: ten males with SCI and 11 able-bodied males (AB group) participated in this study. Two maximal graded exercise tests were performed, starting at 10 watts and increasing the workload by 10 watts every minute until exhaustion. Results: the AB group achieved lower workloads and absolute VO_2 values than the SCI group during the HB test (all $p < 0.05$). The submaximal values of the relative VO_2 peak and RER at workloads between 40-90 watts showed significant differences between SCI and AB on HB and ACr. Significant linear relationships between workload and relative VO_2 peak were found during the HB test ($p < 0.001$). Conclusions: these findings demonstrate that there are different physiological responses between adults with and without SCI when performing maximal and submaximal arm-ergometry. Interestingly, higher VO_2 peak and workloads were achieved by the SCI group. In addition, specific prediction equations derived from the current study can be used to calculate the relative VO_2 peak in handbikers with and without SCI.
Keywords: handcycling; ergometry; spinal cord injury; wheelchair; disability; sport.

Resumen. Introducción: el consumo de oxígeno (VO_2) es una de las variables más importantes en el estudio de la respuesta al ejercicio en personas con y sin lesión medular (SCI; AB). Objetivo: en este estudio se analizaron las respuestas fisiológicas en hombres adultos con y sin SCI al realizar pruebas de esfuerzo máximas en un ergómetro de brazos asincrónico (ACr) en sedestación y en un ergómetro de brazos sincrónico (HB) en posición supina. Métodos: diez hombres con SCI y 11 sin SCI participaron en este estudio. Dos pruebas de esfuerzo gradual fueron realizadas por cada participante, iniciando a 10 watts e incrementando la carga 10 watts cada minuto. Resultados: el grupo sin SCI alcanzó cargas y VO_2 menores que los participantes con SCI durante el test en HB ($p < 0.05$). Los valores submáximos para el VO_2 relativo y el RER a cargas de 40-90 watts fueron estadísticamente diferentes entre los grupos en ambos tests. Se observó una correlación lineal entre las cargas de trabajo y el VO_2 relativo durante el test en HB ($p < 0.001$). Conclusiones: los resultados obtenidos en este estudio demuestran que existen respuestas fisiológicas diferentes entre personas con y sin SCI cuando realizan pruebas de esfuerzo con cargas máximas y submáximas. Llamativamente, el grupo SCI alcanzó mayores cargas de trabajo y VO_2 que los no SCI. Finalmente, se presentan dos ecuaciones específicas para obtener el VO_2 de manera indirecta en personas con y sin SCI mediante el uso de un HB.
Palabras clave: handbike; ergometría; lesión medular; silla de ruedas; discapacidad; deporte.

Introduction

Physical activity significantly reduces cardiovascular disease-related morbidity and mortality in general population (Kohl et al., 2012; Lee et al., 2012). Moreover, it was found that everyday physical activity may have an important role in the fitness and health of people with spinal cord injury (SCI) (Nooijen et al., 2012). Also, some studies found that increasing the physical activity levels of people with SCI will promote improvements in their physical fitness, will reduce the risk of cardiovascular disease and will improve their lipid profiles (Manns, McCubbin, & Williams, 2005; Nooijen et al., 2012). Nevertheless, the physical activity level of people with SCI was found to be lower than the physical activity levels of able-bodied (AB) people (van den Berg-Emons et al., 2008).

The partial or total loss of motor function after a SCI results in lower limb deconditioning and extreme physical inactivity below the level of the lesion. The autonomic nervous system (sympathetic and parasympathetic) control heart rate (HR), and blood pressure. After suffering a SCI, descendent pathways are interrupted and spinal circuits become unable to generate sympathetic activity. Sympathetic hypoactivity results in low HR, reflex bradycardia and rarely cardiac arrest, low resting blood pressure, orthostatic hypotension, loss of regular adaptability, loss of diurnal fluctuation of blood pressure and disturbed reflex control. In addition, arteries show marked remodeling and changes in vascular function, both below and above the level of the lesion (Taylor, 2016).

In AB persons, a redistribution of blood takes place diverting blood from inactive tissues to supply the working muscles. Cardiac output is also increased because of an increase in systolic volume and HR. These vasoregulatory mechanisms are attributable to the actions of the sympathetic nervous system, which in persons with SCI is either completely or partially absent in direct relation to the level of the spinal cord lesion. This results in reduced HR response and myocardial contractility, which greatly limits maximal cardiac output and stroke volume and thus the potential to

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improve cardiovascular fitness. In addition, the paralyzed lower limbs are unable to contribute to venous return during exercise. This lack of muscle pump with consequent blood pooling in the lower limbs reduces end-diastolic volume as a result of reduced systemic filling pressure. All these factors, in accordance with the Frank-Starling mechanism, combine to produce a lower stroke volume compared with AB persons under similar exercise conditions (Taylor, 2016)

In recent years, handcycling has established itself as an alternative for wheelchair propulsion and also as a popular sports discipline (Dallmeijer, Ottjes, De Waardt, & van der Woude, 2004), used for practice, recreational activities and outdoor mobility in people with lower limb impairments. In this population there is an increasing need and demand for accessible sports in order to aid post-SCI rehabilitation, raise quality of life (QoL) and increase longevity (Kawanishi & Greguol, 2013; Recio et al., 2013). Handcycling represents an alternative propulsion system for wheelchair users with SCI below level C5 and for AB people wishing to ride a bike using only their arms (Valent et al., 2008).

Handcycling causes less strain and is more effective than hand-rim-propelled or lever-propelled wheelchairs (Dallmeijer, Zentgraaff, Zijp, & Van der Woude, 2004; Gass & Camp, 1984; Hintzy, Tordi, & Perrey, 2002; Mukherjee & Samanta, 2001), and its energy cost is also lower because of the reduction in mechanical strain (Valent et al., 2008; van Drongelen, van den Berg, Arnet, Veeger, & van der Woude, 2011). However, despite its increasing popularity as a competitive and recreational sport (Hettinga et al., 2013), little is currently known about its physiological and performance characteristics (Lovell, Shields, Beck, Cuneo, & McLellan, 2012).

Cardiorespiratory fitness is a health-related component of physical fitness defined as the ability of the circulatory, respiratory, and muscular systems to supply oxygen during sustained physical activity (Bassett & Howley, 2000). Peak aerobic capacity, which is usually expressed as the maximal oxygen uptake (VO_2 max), is normally measured by exercise tests such as treadmill; cycle ergometer or arm crank ergometer. Maximal oxygen uptake may be one of the most important variables in the study of the responses of SCI and AB people to physical exercise, and the results achieved during its assessment serve as a diagnostic and prognostic health indicator in clinical settings; and is frequently used in the development of an exercise prescription (Laukkanen et al., 2009; Lee, Artero, Xuemei Sui, & Blair, 2010; Lin et al., 2015). Because the direct testing procedure is rather complicated for larger populations, time-consuming and requires relatively expensive equipment, indirect prediction of the VO_2 peak in people with SCI will help to accurately recommend exercise intensities when practicing handbike (HB).

As far as we know, there is sparse information about maximal and submaximal physiological responses in adults with and without SCI during incremental exercise tests and no prediction equation to estimate VO_2 by means of a graded exercise test in people with SCI has been developed. Therefore, the primary purpose of this study was to compare maximal and submaximal physiological responses in a group of males with and without SCI when performing an incremental exercise test until exhaustion, with an asynchronous arm crank ergometer or a recumbent synchronous HB ergometer. The second purpose of this study was to develop VO_2 max prediction equations based on the workload achieved by the participants.

Materials and Methods

Study Design and Participants

This cross-sectional study included 10 adult males with SCI (SCI group) and 11 adult males without SCI (AB group). Neurological examination showed SCI participants' lesions to be chronic (> 1-year post-injury). According to the American Spinal Injury Association (ASIA) neurological classification, 6 participants showed pattern A (no motor or sensory function below the neurological level), 1 participants pattern B (sensory but not motor function is preserved below the neurological level), 3 participant pattern C (motor and sensory function preserved below the neurological level, with muscle grade less than 3). On average, the participants with SCI were wheelchair dependent for 8.5 ± 3.9 years, and they were active in wheelchair sports for 7.4 ± 3.5 years. The mean weekly all-sport activity time was 7.6 ± 2.5 hours, with handbike-specific training of 6.1 ± 3.7 hours. All participants had prior practical experience in wheelchair and HB exercise. All SCI participants used a hand-propelled wheelchair as a primary mean of locomotion. The characteristics and the anthropometric data of the AB and SCI groups are shown in table 1.

This study was approved by the Institutional Review Board (IRB00003099) and follows the Helsinki guidelines for ethical behavior. All participants signed an informed consent form before the start of the study.

Table 1.
Characteristics of the SCI and AB groups.

Variables	AB group (n = 11) Mean ± SD	SCI group (n = 10) Mean ± SD	*p*-value
Age (years)	34.0 ± 10	35 ± 9	0.873
Height (m)	1.74 ± 0.06	1.77 ± 0.07	0.255
Weight (kg)	81.36 ± 11.16	73.10 ± 11.19	0.107
BMI ($kg \cdot m^{-2}$)	26.83 ± 2.56	23.25 ± 3.57	**0.016**
Injury level			
Cervical	-	1 (C7)	
Thoracic	-	8 (1 T3; 2 T4; 1 T9; 2 T10; 2 T11)	
Lumbar	-	1 (L2)	

Values are presented as mean ± standard deviation (SD) or number. Statistically significant values are shown in bold ($p < 0.05$). Abbreviations: BMI: Body mass index; SCI: Spinal cord injury; AB: Able-bodied.

Cardiorespiratory Fitness Assessment

All participants performed two maximal incremental cardiopulmonary exercise tests (CPET) on two different days, 7 days apart. The order of the ergometers to be used for each CPET was randomly determined by toss of a coin. One CPET was carried out on an asynchronous arm crank ergometer (ACr) (Angio, Lode, Gröningen, Netherlands), with the participants sitting on a wheelchair (figure 1); whereas the other CPET was performed on a recumbent synchronous HB (Shark RS, Quickie, Heidelberg, Germany), which was fixed to a LeMond Revolution Bicycle Trainer (LeMond Bicycles LLC, Minneapolis, USA) and the SRM power-meter system (Science model, SRM, Jülich, Germany) was used to measure the workload during the test (figure 1). Different studies have concluded that the SRM system is a valid system to measure the supplied power during cycling (Gardner et al., 2004; Martin, Milliken, Cobb, McFadden, & Coggan, 1998; Smith, Davison, Balmer, & Bird, 2001).

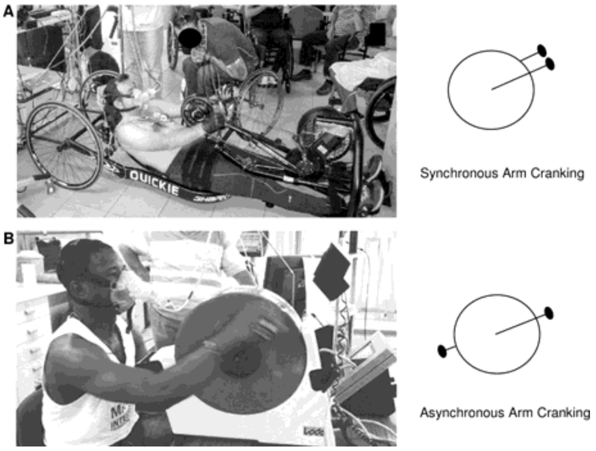

Figure 1. The two types of maximal incremental cardiopulmonary exercise tests performed in this study: (A) recumbent synchronous arm cranking test and (B) seated asynchronous arm cranking test.

During the CPET, the initial workload was set-up at 10 watts and increased by 10 watts each minute until exhaustion. Peak values were recorded as the highest value during the last 30 s of exercise. Peak effort was ascertained by a plateau in HR or when the person achieved a peak respiratory exchange ratio (RER) ≥ 1.1. Pulmonary gas exchange was measured breath-by-breath with an automatic gas analysis system (Metasys TR-plus, Brainware SA, La Valette, France) equipped with a pneumotachometer and making use of a two-way mask (Hans Rudolph, Kansas, USA). The assessed parameters were: absolute oxygen uptake (VO_2, L•min^{-1}), relative oxygen uptake (relative VO_2, ml•kg^{-1}•min^{-1}), expired CO_2 (VCO_2, L•min^{-1}), RER, pulmonary ventilation (VE, L•min^{-1}), tidal volume (VT, L•min^{-1}), respiratory rate (RR, breath•min^{-1}); ventilatory equivalent for O_2 ($VEqO_2$), ventilatory equivalent for CO_2 ($VEqCO_2$); fraction of expired O_2 (FEO_2 %) and fraction of expired CO_2 ($FECO_2$ %). Gas and volume calibrations were performed before each test, according to the manufacturer's guidelines. Twelve-lead electrocardiogram and HR were continuously monitored during the tests (CardioScan v.4.0, DM Software, Stateline, Nevada, USA). All tests were conducted during the morning at a room temperature of 22-24ºC, and relative physical humidity between 55% and 65%.

Statistical Analysis

The Kolmogorov-Smirnov test was used to check the normality of the distributions of the different outcome variables. Group differences and the effect of the testing condition (HB vs. ACr) on each dependent variable were analyzed with 2 x 2 (group-by-condition) analysis of variance for repeated measures. When the interaction was significant, between-group differences at each level were examined with independent samples Student's *t*-test, and each group's responses to the test conditions were examined with paired samples *t*-tests.

Since the data were normally distributed, a linear mixed model was used to analyze relationships between the variables at submaximal loads (all loads between 10 and 90 watts). The linear mixed model is an extension of regression and analysis of variance and allows the modelling of the dependencies in the observations (repeated measurements).

Relative VO_2 prediction equations were developed from workloads achieved during the HB test by the participants using a linear regression. A significance level of $p < 0.05$ was used for all statistical analyses. The analyses were performed using the SPSS v.22 (SPSS Inc., Chicago, USA).

Results

The characteristics of the participants are presented in Table 1. The mean value of the BMI was significantly higher in the AB group than the SCI group ($p = 0.016$). Not significant differences in age, height or body weight were observed between groups.

Maximal Cardiorespiratory Values

Table 2 depicts the maximal mean values and statistical differences of the CPET on HB and ACr for both groups.

Table 2.
Maximal values in the two groups with the different ergometers.

Variables	HB Test			ACr Test		
	AB group Mean ± SD	SCI group Mean ± SD	p_1	AB group Mean ± SD	SCI group Mean ± SD	p_2
Maximal Workload (Watts) ‡	101.36 ± 22.81	157.50 ± 43.98	**0.001**	112.73±22.84	136.50±43.23	0.114
VO_2 peak (L•min^{-1}) *	1.94 ± 0.52	2.93 ± 0.79	**0.003**	2.26 ± 0.58	2.83 ± 0.86	0.089
Relative VO_2 peak (ml•kg^{-1}•min^{-1})*	24.20 ± 7.22	40.42 ± 10.32	**<0.001**	28.04 ± 6.98	39.07 ± 11.28	**0.014**
VCO_2 (L•min^{-1})	2.61 ± 0.69	3.32 ± 1.01	0.092	2.67 ± 0.57	3.16 ± 0.75	0.212
RER *	1.35 ± 0.18	1.13 ± 0.10	**0.002**	1.19 ± 0.09	1.10 ± 0.09	**0.041**
HR (beats•min^{-1}) *	148 ± 19	167 ± 17	**0.022**	158 ± 28	165 ± 22	0.482
VE (L•min^{-1})	78.19 ± 20.99	113.21 ± 28.55	**0.004**	85.61 ± 23.61	99.22 ± 29.13	0.252
V_T (L•min^{-1})	2.00 ± 0.63	2.01 ± 0.42	0.975	2.22 ± 0.56	1.85 ± 0.49	0.121
RR (breath•min^{-1})	38.55 ± 15.29	51.40 ± 10.72	**0.040**	35.45 ± 6.27	49.20 ± 8.27	**< 0.001**
$VEqO_2$	40.81 ± 7.30	38.92 ± 5.19	0.505	38.42 ± 7.72	35.26 ± 4.30	0.267
$VEqCO_2$	30.15 ± 4.81	34.44 ± 3.34	**0.030**	32.10 ± 5.56	32.15 ± 2.46	0.979
FEO_2 (%)	17.67 ± 0.52	17.81 ± 0.48	0.538	17.60 ± 0.67	17.47 ± 0.39	0.625
$FECO_2$ (%)	4.11 ± 0.55	3.57 ± 0.43	**0.023**	3.89 ± 0.68	3.83 ± 0.31	0.811

Values are presented as mean ± standard deviation (SD). Abbreviations: AB: Able-bodied; SCI: spinal cord injury; HB: handbike; ACr: arm asynchronous ergometer; VO_2: oxygen uptake; VCO_2: carbon dioxide production; RER: respiratory exchange ratio; HR: heart rate; VE: ventilation; V_t: tidal volume; RR: respiratory rate; $VEqO_2$: ventilatory equivalent for O_2; $VEqCO_2$: ventilatory equivalent for CO_2; FEO_2: fraction of expired O_2; $FECO_2$: fraction of expired CO_2.
p_1 Significant differences ($p < 0.05$) between AB vs SCI participants on the HB.
p_2 Significant differences ($p < 0.05$) between AB vs SCI participants on the ACr.
* Significant differences ($p < 0.05$) between HB test vs. ACr test in AB participants.
‡ Significant differences ($p < 0.05$) between HB test vs. ACr test in SCI participants.

A significant interaction between group and test condition was found for the maximal workload ($p = 0.001$). Also, there was a significant main effect of group ($p = 0.011$). In the HB test, the AB group showed lower values respect the SCI group ($p = 0.001$). The SCI group reported lower values for the ACr test respect the HB test ($p = 0.002$).

The absolute VO_2 peak did not show a significant interaction between group and test condition ($p = 0.058$). There was a significant main effect of group ($p = 0.013$). The SCI group showed higher values of absolute VO_2 peak than the AB group on the HB test ($p = 0.003$). The AB group showed lower values on the HB test respect the ACr test ($p = 0.037$).

There was no significant interaction between group and test condition for relative VO_2 peak ($p = 0.064$). There was a significant main effect of group ($p = 0.002$). The SCI group presented significantly higher values of relative VO_2 peak than the AB group on both ergometers ($p < 0.001$ for HB test; $p = 0.014$ for ACr test). The AB group showed lower values on the HB test respect the ACr test ($p = 0.048$).

Regarding the maximal HR, the AB group reached significantly lower values than the SCI group on HB test (AB group = 148 ± 19 beats•min^{-1} vs SCI group = 167 ± 17 beats•min^{-1}; $p = 0.022$). Also, the AB group achieved significantly higher values of HR during the ACr test than during the HB test ($p < 0.001$).

Submaximal Cardiorespiratory Values

Submaximal variables with significant differences between SCI and AB groups on HB and ACr tests at all workloads ranging from 10 to 90 W are shown in table 3 (absolute VO_2 peak; relative VO_2 peak, RER and HR), table 4 ($VEqO_2$, $VEqCO_2$) and figures A1-A6.

The RER of the SCI group was significantly lower during both the HB and ACr tests at workloads between 30 to 90 W (all $p < 0.050$). Also, at 20 W the RER of the SCI group during the ACr test was significantly lower than the AB group ($p = 0.006$).

At workloads between 10 to 70 W, the SCI group achieved higher HRs during the ACr test than during the HB test (all $p < 0.050$). In addition, during the ACr test at workload between 20 to 70 W, the SCI group achieved higher HRs values than the AB group (all $p < 0.050$).

Table 3.
Submaximal cardiorespiratory data for the two groups for the different ergometers.

Variables	Workload (W)	HB Test: AB group mean ± SE	HB Test: SCI group mean ± SE	ACr Test: AB group mean ± SE	ACr Test: SCI group mean ± SE	
VO_2 peak ($L•min^{-1}$)	10	0.55 ± 0.07	0.57 ± 0.07	0.57 ± 0.07	0.58 ± 0.07	
	20	0.67 ± 0.07	0.78 ± 0.07	0.63 ± 0.07	0.81 ± 0.07	
	30	0.74 ± 0.07	0.80 ± 0.07	0.73 ± 0.07	0.92 ± 0.07	*4*
	40	0.86 ± 0.07	0.99 ± 0.07	0.87 ± 0.07	1.06 ± 0.07	
	50	0.99 ± 0.07	1.08 ± 0.07	1.00 ± 0.07	1.27 ± 0.07	*2; 4*
	60	1.10 ± 0.07	1.22 ± 0.07	1.13 ± 0.07	1.41 ± 0.07	*2; 4*
	70	1.20 ± 0.07	1.37 ± 0.07	1.25 ± 0.07	1.57 ± 0.07	*2; 4*
	80	1.36 ± 0.07	1.54 ± 0.08	1.38 ± 0.07	1.71 ± 0.07	*2; 4*
	90	1.49 ± 0.07	1.69 ± 0.08	1.51 ± 0.07	1.79 ± 0.08	*2*
Relative VO_2 peak ($ml•min^{-1}•Kg^{-1}$)	10	6.89 ± 0.85	7.81 ± 0.89	7.05 ± 0.85	8.09 ± 0.89	
	20	8.28 ± 0.85	10.59 ± 0.89	7.76 ± 0.85	11.00 ± 0.89	*2*
	30	9.31 ± 0.85	10.98 ± 0.89	9.06 ± 0.85	12.61 ± 0.89	*2; 4*
	40	10.76 ± 0.85	13.58 ± 0.89	10.87 ± 0.85	14.56 ± 0.89	*1; 2*
	50	12.32 ± 0.85	14.79 ± 0.89	12.53 ± 0.85	17.48 ± 0.89	*1; 2; 4*
	60	13.67 ± 0.85	16.84 ± 0.89	13.99 ± 0.85	19.54 ± 0.89	*1; 2; 4*
	70	14.99 ± 0.87	18.83 ± 0.89	15.54 ± 0.85	21.48 ± 0.89	*1; 2; 4*
	80	16.88 ± 0.89	21.46 ± 0.94	17.28 ± 0.87	23.86 ± 0.91	*1; 2; 4*
	90	18.51 ± 0.91	23.51 ± 0.94	18.84 ± 0.87	25.30 ± 0.94	*1; 2; 4*
RER	10	0.91 ± 0.03	0.83 ± 0.03	0.92 ± 0.03	0.85 ± 0.03	
	20	0.86 ± 0.03	0.79 ± 0.03	0.92 ± 0.03	0.80 ± 0.03	*2; 3*
	30	0.91 ± 0.03	0.82 ± 0.03	0.90 ± 0.03	0.82 ± 0.03	*1; 2*
	40	0.94 ± 0.03	0.81 ± 0.03	0.90 ± 0.03	0.80 ± 0.03	*1; 2*
	50	1.00 ± 0.03	0.85 ± 0.03	0.92 ± 0.03	0.83 ± 0.03	*1; 2; 3*
	60	1.09 ± 0.03	0.86 ± 0.03	0.97 ± 0.03	0.86 ± 0.03	*1; 2; 3*
	70	1.15 ± 0.03	0.91 ± 0.03	1.01 ± 0.03	0.89 ± 0.03	*1; 2; 3*
	80	1.19 ± 0.03	0.91 ± 0.03	1.06 ± 0.03	0.91 ± 0.03	*1; 2; 3*
	90	1.20 ± 0.03	0.96 ± 0.03	1.10 ± 0.03	0.93 ± 0.03	*1; 2; 3*
HR ($beats•min^{-1}$)	10	74.73 ± 4.20	78.70 ± 4.41	77.91 ± 4.20	88.20 ± 4.41	*4*
	20	80.00 ± 4.20	86.50 ± 4.41	81.45 ± 4.20	96.80 ± 4.41	*2; 4*
	30	86.09 ± 4.20	90.90 ± 4.41	85.82 ± 4.20	102.90 ± 4.41	*2; 4*
	40	94.82 ± 4.20	97.80 ± 4.41	93.27 ± 4.20	107.20 ± 4.41	*2; 4*
	50	102.27 ± 4.20	104.00 ± 4.41	99.64 ± 4.20	115.00 ± 4.41	*2; 4*
	60	109.82 ± 4.20	112.20 ± 4.41	106.00 ± 4.20	121.70 ± 4.41	*2; 4*
	70	118.40 ± 4.26	118.00 ± 4.41	112.91 ± 4.20	128.60 ± 4.41	*2; 4*
	80	125.82 ± 4.33	127.52 ± 4.55	124.90 ± 4.26	133.19 ± 4.47	
	90	132.60 ± 4.41	136.27 ± 4.55	132.70 ± 4.26	140.11 ± 4.55	

Values are presented as mean ± standard error (SE). Abbreviations: AB: Able-bodied; SCI: spinal cord injury; HB: recumbent synchronous handbike ergometer; ACr: asynchronous arm crank ergometer; VO_2: oxygen uptake; RER: respiratory exchange ratio.
1: HB-AB vs. HB-SCI significant difference ($p < 0.05$).
2: ACr-AB vs. ACr-SCI significant difference ($p < 0.05$).
3: HB-AB vs. ACr-AB significant difference ($p < 0.05$).
4: HB-SCI vs. ACr-SCI significant difference ($p < 0.05$).

Indirect Prediction of Relative VO_2.

In the HB test, a significant linear relationship was found between workload and relative VO_2 peak for the AB group ($r^2 = 0.977$, $p < 0.001$). Figure 2 depicts the linear relationship between relative VO_2 peak and workload for both groups. The following regression equation can be used to predict the relative VO_2 in AB people practicing HB:

$$VO_2\ (ml•kg^{-1}•min^{-1}) = 3.383 + 0.183 • workload\ (W)$$

Also, for the SCI group a significant linear relationship was found for workload and relative VO_2 peak during the HB test ($r^2 = 0.996$, $p < 0.001$). For SCI people, the following equation can be used to predict the relative VO_2 when practicing HB:

$$VO_2\ (ml•kg^{-1}•min^{-1}) = 5.592 + 0.196 • workload\ (W)$$

Table 4.
Submaximal cardiorespiratory data for the two groups for the different ergometers.

Variables	Workload (W)	HB Test: AB group mean ± SE	HB Test: SCI group mean ± SE	ACr Test: AB group mean ± SE	ACr Test: SCI group mean ± SE	
$VEqO_2$	10	28.62 ± 1.33	29.29 ± 1.39	29.52 ± 1.33	31.32 ± 1.39	
	20	26.07 ± 1.33	26.68 ± 1.39	28.79 ± 1.33	28.33 ± 1.39	*3*
	30	26.68 ± 1.33	28.19 ± 1.39	26.92 ± 1.33	27.55 ± 1.39	
	40	27.49 ± 1.33	26.54 ± 1.39	25.97 ± 1.33	25.91 ± 1.39	
	50	28.99 ± 1.33	27.66 ± 1.39	26.07 ± 1.33	25.59 ± 1.39	*3*
	60	31.26 ± 1.33	28.14 ± 1.39	26.96 ± 1.33	26.40 ± 1.39	*3*
	70	33.81 ± 1.36	29.17 ± 1.39	28.28 ± 1.33	27.46 ± 1.39	*1; 3*
	80	34.48 ± 1.40	28.81 ± 1.48	30.05 ± 1.36	27.71 ± 1.43	*1; 3*
	90	34.50 ± 1.45	29.69 ± 1.48	32.64 ± 1.36	27.97 ± 1.48	*1; 2*
$VEqCO_2$	10	31.85 ± 1.07	35.88 ± 1.12	32.00 ± 1.07	38.81 ± 1.12	*1; 2; 4*
	20	30.45 ± 1.07	33.74 ± 1.12	31.32 ± 1.07	35.26 ± 1.12	*1; 2*
	30	29.52 ± 1.07	34.30 ± 1.12	29.80 ± 1.07	33.57 ± 1.12	*1; 2*
	40	29.19 ± 1.07	32.55 ± 1.12	28.85 ± 1.07	32.27 ± 1.12	*1; 2*
	50	29.09 ± 1.07	32.50 ± 1.12	28.31 ± 1.07	30.51 ± 1.12	*1*
	60	28.61 ± 1.07	32.49 ± 1.12	27.75 ± 1.07	30.71 ± 1.12	*1*
	70	29.43 ± 1.10	32.10 ± 1.12	27.99 ± 1.07	30.60 ± 1.12	
	80	28.95 ± 1.13	31.50 ± 1.20	28.10 ± 1.10	30.09 ± 1.16	
	90	28.56 ± 1.18	30.77 ± 1.20	29.38 ± 1.10	29.82 ± 1.20	

Values are presented as mean ± standard error (SE). Abbreviations: AB: Able-bodied; SCI: spinal cord injury; HB: recumbent synchronous handbike ergometer; ACr: asynchronous arm crank ergometer; $VEqO_2$: ventilatory equivalent for O_2; $VEqCO_2$: ventilatory equivalent for CO_2.
1: HB-AB vs. HB-SCI significant difference ($p < 0.05$).
2: ACr-AB vs. ACr-SCI significant difference ($p < 0.05$).
3: HB-AB vs. ACr-AB significant difference ($p < 0.05$).
4: HB-SCI vs. ACr-SCI significant difference ($p < 0.05$).

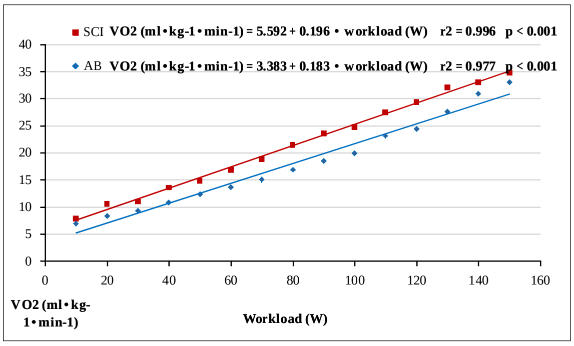

Figure 2. Evolution of the relative VO_2 data for the AB and SCI groups during the handbike test. Abbreviations: AB: Able-bodied; SCI: spinal cord injury.

Discussion

In this study, significant differences were found between the SCI and AB groups in response to exercise at maximal and submaximal workloads. The response in both groups differed according to the ergometer used. These differences (i.e., those related to the existence of SCI or the type of ergometer used) should be taken into account when applying workloads on physical exercise programs designed to improve health in these two populations.

In persons with SCI, cardiovascular diseases are the leading cause of morbidity and mortality (Myers, Lee, & Kiratli, 2007; Phillips & Krassioukov, 2015). Physical activity is an important tool that helps to counteract the deleterious effect of this chronic condition and also helps to improve functional capacity and reduce risk factors in this population (Tweedy et al., 2017). By the results obtained in our study, the workloads that can be applied when practicing HB would be able to promote functional and metabolic improvements (Hooker & Wells, 1989).

We consider handcycling as an extremely positive mode of training and exercise. It allows performing safety and healthy workout in outdoor conditions that may increase the participation and adherence to practicing sport. Also, it is an inclusive sport that can be practiced by persons with and without disability and may help to improve the health and quality of life of the handbikers (De Groot, Dallmeijer, Post, Angenot, & Van Der Woude, 2008; Tomasone, Wesch, Ginis, & Noreau, 2013).

Keyser et al. (1999) found that VO_2 peak was significantly higher in their AB group, probably due to their greater functional muscle mass. On the contrary, in our study, the participants with SCI had higher maximal values of VO_2 peak and achieved higher workloads than the AB group. The differences with the study by Keyser et al. (1999) could be due to the different ergometers used in their study and the lower training status of their participants in comparison with the participants of the current study.

The SCI group was able to achieve similar VO_2 peak on both ergometers. However, the maximal workload achieved on the HB ergometer was around 15 % higher. As they were able to achieve higher workloads by using similar energy pathways, we hypothesize that the SCI participants had a higher mechanical efficiency on the HB that help them to be more economical and reduced the energy demand (Faupin, Borel, Meyer, Gorce, & Watelain, 2013). This could be confirmed by the values observed in the HR, where the SCI group presents similar maximum values for both tests, and higher than the AB group during the HB test.

Interesting, in our study the physiological adaptation of the HR to maximal exercise in our participants with SCI is similar to that observed in our AB group when using the ACr ergometer. Nevertheless, during the HB test the HR response of the SCI group was different respect the AB group, which could be due to a more efficient technique and greater familiarization with the synchronous HB ergometer.

Due to the reduce effect of the skeletal muscle pump and the impaired autonomic control of the circulation below the level of the injury, it is suggested that during a HB test in the recumbent position, there is a better venous return, increasing the end-diastolic volume, and allowing a better blood volume distribution (McLean & Skinner, 1995). Nevertheless, previous studies have explored the possibility of improving maximal exercise performance in individuals with SCI by supporting the redistribution of blood during arm exercise, using an anti-gravity suit, performing the exercise in a supine position, a stocking and abdominal binder or functional electrical stimulation but maximal performance did not improve under these conditions (Haisma et al., 2006; M. Hopman, Dueck, Monroe, Philips, & Skinner, 1998; Hopman, 1994). This may suggest that the limitation in peak oxygen uptake in individuals with SCI without training is not located peripherally rather than centrally.

The impact of the trunk and its muscular stabilization require a high static workload and, as several authors suggest, reduces mechanical efficiency during ACr propulsion in adults with SCI (Dallmeijer, Zentgraaff, et al., 2004; Hintzy et al., 2002; van der Woude et al., 2008). On the contrary, the fact of being able to use the stabilizing muscles of the trunk and the lower fatigue of the triceps brachii during the ACr test (Hopman, van Teeffelen, Brouwer, Houtman, & Binkhorst, 1995), may allowed the AB participants to achieve higher VO_2 peak and peak power during the asynchronous arm crank test.

Some authors suggest that during synchronous arm ergometry tests there may be a better stabilization of the upper body in individuals with reduced trunk muscle activation and better inter and intra-muscular coordination, which leads to a higher and more economical function at equal energy demand (Abel, Vega, Bleicher, & Platen, 2003). Also, the flexion and extension movement of shoulders and elbows during the synchronous arm ergometry is more like the movement that users of wheelchair perform in their daily life. The specificity of the synchronous movement may also contribute to obtaining better results during synchronous arm ergometry in adults with SCI.

At submaximal workloads, we observed a higher oxygen uptake and lower values of the RER in the SCI group than in the AB group. These results demonstrate the adaptation of the SCI group to the physical exercise, which allows them to work aerobically at higher loads than the AB group. In contrast to the study by Jacobs et al. (2013) (Jacobs, Burns, Kressler, & Nash, 2013), who found that at workloads lowers than 30-40% of the VO_2 peak there is a greater energy contribution coming from fat oxidation, we hypothesize that the participants with SCI who took part in this study were able to oxidize greater amounts of fat and use carbohydrates at higher loads because of their training adaptation (Theisen, 2012). This hypothesis should be studied in the future to delimit to what intensities of exercise the crossover is found in trained people with SCI.

When comparing the participants with and without spinal cord injury in our study, it is possible to observe that SCI group has a higher utilization of lipids as a source of energy at submaximal workloads. While the percentage of carbohydrates/fats in the SCI group ranged from approximately 30/70% at 20 W to approximately 53/47% at 60 W, in the AB these percentages were approximately 53/47% at 20 W and approximately 100/0% at 60 W. Apparently, the results obtained in our study indicate that the participants with SCI have a greater metabolic efficiency, which, as aforementioned, could be due to the adaptations promoted by the type of exercise that people with SCI conduct.

Keeping our results in mind, future research studies should explore whether changes in the energy source for the metabolism of exercise are dependent on changes in the maximal aerobic power, which could explain that the SCI group was using higher proportion of lipids because in relation to the maximal workload the submaximal workloads were lower. Another possibility, is that the muscle fibers of the participants with SCI have undergone changes, favoring the development of type I fibers and therefore of oxidative capacity or, thanks to functional modification of type II fibers due to continuous aerobic effort that SCI persons do.

The metabolic differences between the SCI and AB groups at different workloads point out the necessity of using different equations to indirectly calculate the metabolic needs of adults with and without SCI when practicing HB.

Following the Exercise and Sports Science Australia position statement on exercise and spinal cord injury (Tweedy et al., 2017), adults with SCI should perform ≥ 30 min of moderate (≥ 3 MET) aerobic exercise on ≥ 5 d/week to affect positively their health and quality of life. In our study, for intensities of 3 METs there would be a between-group difference of 16% with respect to the workload [Table 3: VO_2

(L•min^{-1}) = 1.20 at 70 W for AB group vs. VO_2 (L•min^{-1}) = 1.22 at 60 W for SCI group]. The difference in the time dedicated to the physical activity by the persons with SCI, having a higher metabolic cost for the same load, should be lower. Thus, for the anthropometric characteristics of our participants (Table 1), the AB group should perform 260 min of handcycling at an intensity of 3 MET to achieve a weekly energy expenditure of approximately 1000 kcal/week, while the SCI group should perform 220 min at the same intensity to achieve the same metabolic cost.

Because of the fact that the SCI population perform all their daily life activities with their upper limbs, adjusting the time and intensity of the exercise as much as possible will reduce the prevalence of injuries and shoulder pain due to overuse (Tweedy et al., 2017). It is highly recommendable to be extremely cautious when planning the training of persons with SCI to avoid leading the participants into a vicious cycle of injuries and abandonment of the sport practice, with the consequent deleterious effect on their health and quality of life.

Furthermore, we consider that HB is an important tool which facilitates the participation of people with lower limbs impairments in physical exercise programs, allowing them to maintain and improve their aerobic and health condition. Nevertheless, new studies must be conducted to rigorously evaluate this assumption.

This study presents some limitations. It should be pointed out that due to the relatively small sample size in this study, the results may not be a direct reflection of the entire population with SCI; nevertheless, the number of participants in this study is similar to other studies and reflects a significant proportion of a small population (Alves et al., 2017; Fischer, Tarperi, George, & Ardigò, 2014; Iturricastillo, Yanci, Los Arcos, & Granados, 2016).

Finally, as in the present study females were not included; the results obtained will need to be cautiously interpreted and will warrant confirmation in future studies including females with and without SCI.

Conclusions

In conclusion, differences between adults with and without SCI at maximal and submaximal workloads were observed, with higher VO_2 peak and workloads achieved by the SCI group. We recommend practicing HB with a synchronic arm crank because it is more likely to the movement that persons with SCI perform in their daily life. Secondly, it is a safe exercise that can be practiced by people with and without SCI and may help to build up fitness and muscle strength.

The specific equation derived from the current study will allow calculating accurate prediction of VO_2 peak and may help to prescribe the appropriate intensities in adults with and without SCI practicing HB without the help of a well-equipped laboratory and with a lower cost. In addition, the correct estimation of the workload for an exercise training program may help to avoid excessive overloads of the musculoskeletal system of the shoulders, preventing injuries and abandonment of sports practice.

Finally, future research studies are warranted to investigate the specific causes of the different metabolic and cardiovascular responses to exercise in SCI people, especially at submaximal workloads.

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Conflicts of Interest

The authors declare no conflict of interest.

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