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Original article

Cardiorespiratory Optimal Point application in cardiopulmonary assessment in effort of individuals with spinal cord injury

Aplicação do Ponto Ótimo Cardiorrespiratório na avaliação cardiorrespiratória em esforço de indivíduos com lesão medular

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ABSTRACT

Introduction: Spinal Cord Injury (SCI) is related to low cardiorespiratory fitness and increased cardiovascular morbidity and mortality. In individuals with SCI, the assessment of cardiorespiratory capacity, whose best variable for analysis is maximal oxygen consumption (VO_{2max}), is commonly impaired due to early interruption of effort. Consequently, measurements obtained at submaximal intensities are necessary, such as the cardiorespiratory optimal point (POC). **Objective:** To describe and compare the cardiorespiratory fitness in exertion of individuals with high, low and no LM. **Methods:** Cross-sectional study in participants with incomplete high LM, complete low LM and without LM, performed with progressive tests on a cycle ergometer for upper limbs, considering peak exercise, ventilatory threshold 1 (LV1) and POC. **Results:** Individuals with SCI had lower exercise tolerance and lower peak VO_2 compared to individuals without SCI, despite the fact that all groups reached the end of the exercise equally with a greater contribution of anaerobic metabolism in energy production. As for the analysis of submaximal exertion intensities, individuals with quadriplegia, among the three groups, reached maximum ventilatory efficiency (POC) at higher percentages of peak VO_2. **Conclusion:** Individuals with SCI have lower cardiorespiratory fitness at peak and submaximal exertion intensities when compared to individuals without SCI. Particularly in relation to POC, the higher the level of LM, the greater the ventilatory need to meet the metabolic demands of exercise.

Keywords: people with disability; oxygen consumption; exercise.

RESUMO

Introdução: A Lesão Medular (LM) se relaciona à baixa aptidão cardiorrespiratória e ao aumento da morbimortalidade cardiovascular. Em indivíduos com LM, a avaliação da capacidade cardiorrespiratória, cuja melhor variável para análise é o consumo máximo de oxigênio ($VO_{2máx}$), é comumente prejudicada devido à interrupção precoce do esforço. Consequentemente, as mensurações obtidas em intensidades submáximas se fazem necessárias, como o ponto ótimo cardiorrespiratório (POC). **Objetivo:** Descrever e comparar a aptidão cardiorrespiratória em esforço de indivíduos com LM alta, baixa e sem LM. **Métodos:** Estudo seccional em participantes com LM alta incompleta, LM baixa completa e sem LM, realizado com testes progressivos em cicloergômetro para membros superiores, considerando pico do exercício, limiar ventilatório 1 (LV1) e POC. **Resultados:** Os indivíduos com LM apresentaram menor tolerância ao esforço e menor VO_2 de pico em relação aos indivíduos sem LM, apesar de todos os grupos terem chegado igualmente ao término do exercício com uma maior contribuição do metabolismo anaeróbio na produção de energia. Quanto às análises em intensidades submáximas de esforço, os indivíduos com tetraplegia, dentre os três grupos, foram aqueles que alcançaram a máxima eficiência ventilatória (POC) em percentuais mais altos do VO_2 de pico. **Conclusão:** Indivíduos com LM apresentam menor aptidão cardiorrespiratória no pico e em intensidades submáximas de esforço quando comparados com indivíduos sem LM. Particularmente em relação ao POC, quanto mais alto o nível da LM, maior a necessidade ventilatória para o atendimento das demandas metabólicas do exercício.

Palavras-chave: pessoas com deficiência; consumo de oxigênio; exercício físico.

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Introduction

Spinal cord injury (SCI) is associated with changes in the functioning of several body systems, which may vary according to the height of the injury [1]. In parallel, a higher prevalence of sedentary behavior is described in individuals with SCI due to environmental barriers - such as lack of accessibility - and psycho-emotional barriers, such as demotivation and impaired self-esteem and self-image [2]. Together, these factors contribute to poor cardiorespiratory fitness and increase the risk of health-related complications [3].

Maximum oxygen consumption (VO_{2max}) is the variable that best describes the cardiorespiratory fitness of individuals [4], and higher values are related to a lower risk of cardiovascular morbidity and mortality [5]. It is obtained through the metabolic analysis of ventilatory gases during the performance of a maximum progressive effort, commonly in cycle ergometers selected according to the individual characteristics of the evaluated. In individuals with functional limitations, as in SCI, however, it is common to interrupt the effort due to peripheral factors such as low muscle capacity, limiting the performance of the movement [6]. This makes it difficult to obtain the VO_{2max}, limiting the interpretation of the test results [7]. Faced with this difficulty, Ramos *et al*. [8] proposed the analysis of the lowest value of the ventilatory oxygen equivalent during exercise as an indicator that would represent the highest ventilatory savings for the capture of oxygen and consequent supply to the active musculature. This variable was named "Cardiorespiratory Optimal Point" (COP), with the advantage of obtaining it at submaximal exertion intensity. It is an alternative variable for the analysis of cardiorespiratory capacity, especially in situations where maximum effort is not reached (as in different functional limitations) or is not desirable (as in certain phases of sports training) [9]. After consulting the Pubmed/Medline and Scielo databases using the combination of the "cardiorespiratory optimal point" and "spinal cord injury" terms, no studies were found that had analyzed this variable in the population of individuals with SCI.

The importance of a periodic assessment of the cardiorespiratory capacity of individuals with SCI lies in identifying and acting in different scenarios, including rehabilitation and physical training prescription for sports purposes [10]. Therefore, it is necessary that the measured variables effectively reproduce the reality and the level of physical conditioning so that efficient interventions are selected and the gains maximized. Thus, the objective of the present study is to test the hypotheses: a) individuals with SCI have lower cardiorespiratory fitness than individuals without SCI at different intensities of effort, and b) specifically concerning COP, individuals with SCI have a greater ventilatory need during the exercise.

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Methods

Study and participants

A cross-sectional comparative observational study was carried out with the participation of 27 men aged 18 years or over divided into three groups: incomplete high SCI (QUADRI group; from the fourth to the seventh cervical vertebra; N = 09), complete low SCI (PARA group; first thoracic vertebra to second lumbar vertebra; N = 08) and without SCI (N = 10). All were physically active for at least six months: wheelchair rugby practice in the QUADRI group, wheelchair basketball in the PARA group, and aerobic and strength exercises in the group without SCI. Individuals without SCI were classified as "active" or "very active" by completing the short version of the International Physical Activity Questionnaire (IPAQ) [11]. The groups of participants with SCI were selected for convenience in two sports associations for people with disabilities in Rio de Janeiro, Brazil. Smokers, users of substances that interfere with the heart rate response (for example, beta-blockers, sympathomimetics, and sympatholytics), and those with pain or disabling musculoskeletal limitations for performing the Cardiopulmonary Exercise Test (CPET) were excluded.

The study was approved by the institutional Research Ethics Committee (CAAE: 37041520.4.0000.5235), and all participants signed an informed consent form before participating in the study.

Cardiorespiratory fitness in exertion

To assess cardiorespiratory fitness during exercise, a CPET of increasing intensity was performed on a cycle ergometer for the upper limbs (TopExcite, TechnoGym; Italy). The tests were performed in the morning in a laboratory with controlled temperature (≈ 22° C) and humidity (≈ 60%) [12].

The initial load was 20w with successive increments of 2w or 5w every minute – according to the functionality of the participant's upper limbs – and cycling between 50-60 rpm [13]. Participants were verbally encouraged to exert maximum effort, which was interrupted due to exhaustion or the appearance of one of the criteria defined by the American College of Sports Medicine (2018) [4].

Throughout the test, the participants remained connected to a metabolic analyzer of ventilatory gases (*VO2000, MedGraphics; Brazil*) that allowed the reading of pulmonary ventilation (VE, L/min) and expired oxygen fractions (FeO_2, %) and carbon dioxide ($FeCO_2$, %). Information was recorded breath-by-breath and plotted as a 30-second average. The following variables were calculated: relative and absolute oxygen consumption (VO_2, $mL.kg^{-1}.min^{-1}$, and L/min, respectively) and ventilatory equivalents of oxygen (VE/VO_2) and carbon dioxide (VE/VCO_2). VO_2 was considered maximum if: (I) presence of a plateau in the VO_2 curve concomitant with the increase in effort intensity was observed; (II) respiratory quotient (R) ≥ 1.1; and (III) existence of VT1 [12]. In the absence of VO_{2max}, the highest value presented in the last minute of the test was considered as peak.

Ventilatory threshold 1

Ventilatory threshold 1 (VT1) was identified according to the recommendations proposed by Gaskill *et al.* [14], which include the combination of analysis of three methods: I) ventilatory equivalents of oxygen and carbon dioxide; II) excess carbon dioxide; and III) modified V-slope. Visual inspection to determine VT1 was performed independently by two experienced evaluators. If the difference between the evaluators concerning VO_2 in VT1 was within 3%, the mean value was adopted as the final result. If the difference exceeded 3%, a third evaluator would be asked to determine VT1.

Cardiorespiratory Optimal Point

The Cardiorespiratory Optimal Point (COP) was considered the lowest value of the ventilatory oxygen equivalent (VE/VO_2) during the effort [8]. Relative VO^2 ($mL.kg^{-1}.min^{-1}$), absolute VO_2 (L/min), percentage of peak VO_2, load (w), and effort time (s) relative to COP were also analyzed.

Statistical procedures

Since the eligible sample consisted of all wheelchair rugby athletes from a regional team, a post-hoc calculation of the minimum effect size (f) to be detected was performed for comparison between groups using the G*Power software. Considering a type I error equal to 5% and test power equal to 80% (type II error equal to 20%), a minimum effect size (f) of 0.63 can be detected in the 3 groups comparison, with a total of 27 participants.

The exploratory data analysis was presented by the median and the minimum and maximum values. The distribution of variables was verified using the Shapiro-Wilk test, and after the analysis, it was decided to adopt non-parametric procedures. Comparisons between the three subgroups of the study were made using the Kruskal-Wallis test and the differences identified by the Mann-Whitney test with Bonferroni correction for the three possible combinations of pairs ($p < 0.017$). Comparisons between the QUADRI and PARA groups were made using the Mann-Whitney test. The statistical significance level adopted was 5%, and the analyzes were performed using SPSS 20.0 (*Armonk, NY: International Business Machines Corporation*).

Results

The general characteristics and the practice of physical exercises of the study participants are described in Table I. In comparison with the group without SCI, the QUADRI group had lower body mass, and the PARA group was older. The time of physical exercise practice was similar between the QUADRI and PARA groups and longer than that presented by the group without SCI. There was also no difference between the time of SCI.

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Table I - General characteristics of the study participants, according to the analysis subgroup

	QUADRI (N = 09)	PARA (N = 08)	No SCI (N = 10)	P-value
Age (years)	34 (25-47)	44.5[b] (25-50)	31.5 (22-40)	0.028[1]
Body mass (kg)	69[a] (50.7-80.1)	80.2 (58.9-100.2)	85.6 (71.5-102)	0.008[1]
Height (cm)	180 (171-188.5)	175 (164-184)	181.5 (169-185)	0.277[1]
SCI time (years)	13 (4-24)	6 (3-26)	-	0.114[2]
Time of physical exercise practice (months)	48[c] (6-132)	54[b] (36-60)	12 (6-18)	0.001
Weekly frequency of physical exercise (days/week)	3 (3-3)	2[b] (1-5)	4 (3-5)	0.006

QUADRI = High and incomplete spinal cord injury; PARA = low spinal cord injury; SCI= spinal cord injury; 1Kruskal-Wallis test, statistical significance when $p < 0.05$; [2]Mann-Whitney test, statistical significance when $p < 0.05$; aMann-Whitney test with Bonferroni correction, statistical significance when $p < 0.017$ (QUADRI ≠ PARA); bMann-Whitney test with Bonferroni correction, statistical significance when $p < 0.017$ (PARA ≠ Without SCI); c Mann-Whitney test with Bonferroni correction, statistical significance when $p < 0.017$ (QUADRI ≠ Without SCI)

Table II shows the results related to CPET. The QUADRI and PARA groups presented lower time and total effort load, relative VO_{2peak}, and absolute VO_{2peak}, compared to the group without SCI. The R at the end of the effort, however, did not differ between the three groups. All participants reported interruption of effort due to peripheral fatigue of the upper limbs involved in the movement.

Regarding the COP, the groups showed similarity in terms of time at the moment of reaching ($p = 0.476$) and load ($p = 0.239$). The COP value was lower in the QUADRI group compared to those without SCI and the $\%VO_{2peak}$ in the COP was higher in the QUADRI both in relation to the PARA and in relation to those without SCI. One participant in the QUADRI group presented COP after VT1 (COP time = 03 min: 52s; VT1 time = 02 min: 51s). All other participants presented COP before VT1. Of all study participants, only two in the QUADRI group did not reach VT1. The QUADRI and PARA groups reached this point earlier than those without SCI, as well as with lower loads, VO_2 ($mL.kg^{-1}.min^{-1}$) and VO_2 (L/min). The $\%VO_{2peak}$ in VT1 was higher in the participants of the QUADRI group in relation to the PARA and without SCI.

Table II – Variables related to the cardiopulmonary exercise test of the study participants, according to the analysis subgroup

	QUADRI (N = 09)	PARA (N = 08)	No SCI (N = 10)	P-value[1]
Total effort time (min:s)	08:21[b] (01:43-18:35)	08:39[c] (06:13-21:11)	18:28 (13:09-23:09)	**0.001**
Load at end of effort (w)	40[b] (22-60)	57.5[c] (45-120)	110 (85-135)	**<0.001**
VO_{2peak} (mL.kg^{-1}.min^{-1})	10.2[b] (5.3-16)	15.7[c] (9.6-23.7)	31.9 (22.6-38.6)	**<0.001**
VO_{2peak} (L/min)	0.8[a.b] (0.4-0.9)	1.2[c] (0.9-2.3)	2.9 (1.7-3.7)	**< 0.001**
R	1.1 (0.5-1.4)	1.0 (0.9-1.2)	1.0 (0.8-1.5)	0.725
Time in COP (min:s)	01:51 (00:30-03:55)	01:45 (00:47-04:06)	02:30 (00:30-04:30)	0.476
Load in COP (w)	25 (20-35)	25 (20- 40)	30 (20-40)	0.239
Lower VE/ VO_2 (COP)	23.1[b] (17.5-36.2)	18.8 (14.4-30.8)	16.0 (13.3-20.2)	**0.004**
VO_2 in COP (mL.kg^{-1}.min^{-1})	8.9 (5.5-14.1)	4.9 (0.5-9.5)	8.1 (5.8-12.3)	**0.044**
%VO_{2peak} in COP (%)	85[a.b] (58.6-100)	43.7 (2.3-56.8)	27.4 (22.5-35.0)	**< 0.001**
Time in VT1 (min:s)	02:56[b] (02:20-10:51)	04:18[c] (02:46-13:16)	09:00 (06:30-12:30)	**0.004**
Load on VT1 (w)	30[b] (24-40)	37.5[c] (30-95)	72.5 (50-85)	**0.001**
VO2 in VT1 (mL.kg^{-1}.min^{-1})	9.0[b] (4.2-13.1)	10.2[c] (0.9-14.1)	17.0 (10.5-23.8)	**0.002**
VO2 in VT1 (L/min)	0.7[b] (0.3-1.0)	0.8[c] (0.1-1.3)	1.4 (1.0-2.0)	**0.001**
%VO_{2peak} in VT1 (%)	77.6[a.b] (70.1-87.3)	62.5 (10.3-74.1)	55.4 (43.3-68.8)	**0.001**

QUADRI= High and incomplete spinal cord injury; PARA= low spinal cord injury; SCI= spinal cord injury; 1Kruskal-Wallis test, statistical significance when $p < 0.05$; Mann-Whitney test with Bonferroni correction, statistical significance when $p < 0.017$ (QUADRI ≠ PARA); bMann-Whitney test with Bonferroni correction, statistical significance when $p < 0.017$ (QUADRI ≠ Without SCI); cMann-Whitney test with Bonferroni correction, statistical significance when $p < 0.017$ (PARA ≠ Without SCI)

Discussion

The main findings of the present study include lower exercise tolerance and lower peak VO_2 in participants with SCI compared to individuals without SCI, even though all groups reached the end of the exercise equally with a higher contribution of anaerobic metabolism in the process of energy production (mean R of the groups ≥ 1; $p = 0.725$). About the analysis of submaximal exertion intensities, individuals with quadriplegia reached maximum ventilatory efficiency, that is, COP, at higher percentages of peak VO_2, as well as VT1. This difference was observed both in comparison to individuals with paraplegia and those without SCI. To the authors' knowledge, this was the first approach to the COP application in individuals with SCI.

The lower effort tolerance observed in the SCI group may reflect the lower amount of muscle mass generally presented in the upper limbs of these individuals, especially those with higher injuries in which the loss is more pronounced. These structural losses impact functionality and mobility by the total or partial interruption of sensory and motor information below the lesion level [1]. However, it should be considered that the exercise was performed with the upper limbs, which are highly requested by individuals with SCI for daily commuting, but the movement performed to propel the wheelchair differs from the gesture performed on the cycle ergometer used. Therefore, it is also possible that this difference influenced, in a certain way, the occurrence of early fatigue.

As for VO_2 at the end of the exercise, the differences observed between individuals with and without SCI, in addition to being explained by the amount of muscle mass involved during the test, may also be associated with the modulation of cardiac inotropism by the autonomic nervous system [15]. Through the sympathetic and parasympathetic branches, which, respectively, increase and decrease cardiac function, changes in heart rate and contraction force are observed, for example [16]. Since the sympathetic fibers that innervate the heart originate in the spinal cord, between the first and fifth thoracic vertebrae, and the parasympathetic fibers originate in the vagus nerve, it is concluded that individuals with SCI at these levels have impairments in sympathetic tone and, consequently, in the positive stimulus to cardiac work. According to Draghici and Taylor [17], the damage to the autonomic pathways in the face of an SCI may not be necessarily associated with the level/height of the lesion, or even if it is complete or incomplete. However, considering the origins of the sympathetic and parasympathetic fibers that innervate the heart, the sympathetic control would be more impaired the higher the level/height of the lesion, while the parasympathetic control would remain unchanged.

Impairments in sympathetic control include lower heart rate at submaximal and maximal exertion levels, lower blood pressure, and lower cardiac output. These changes during physical exercise translate into a lower blood supply to the active muscles and, consequently, lower VO_2 [18]. Nightingale *et al.* [19] investigated the cardiorespiratory capacity in effort on a cycle ergometer for upper limbs of patients with cervical SCI, high thoracic SCI, and thoracolumbar SCI, noting differences between the groups both with peak VO_2 and maximal power - that is, how much the higher the lesion height/level, the lower the VO_2 and power. In a study comparing cardiorespiratory capacity under two conditions a) using only the cycle ergometer for upper limbs and b) the cycle ergometer associated with electrical stimulation, an inverse relationship was also observed between the height/level of the lesion and, VO_{2peak} regardless of the condition tested [20]. It is noteworthy that, in the presence of electrical stimulation, the VO_2 values were higher. This same relationship between

SCI level/height was observed in the present study, although without statistical significance in some comparisons.

In the measurements obtained, the COP was one of the moments considered for the cardiorespiratory capacity characterization in submaximal effort intensity. In the study by Ramos and Araújo [21], COP values lower than 22 were shown to be associated with a lower risk of mortality both in healthy individuals and in individuals with chronic diseases. However, it should be noted that the assessment was performed on a cycle ergometer for lower limbs, and this value will not necessarily be the same for exercises performed on other ergometers, such as the treadmill and cycle ergometer for upper limbs. To date, the authors are not aware of a reference point delimitation for the mortality risk classification by analyzing the COP obtained using a cycle ergometer for upper limbs. However, if lower COP values are associated with a lower risk, it can be assumed, in the present study, that the QUADRI group may be at greater risk or, more appropriately, present a worse ventilatory economy since it presented the highest Median COP among the three subgroups evaluated in the study (median value of the QUADRI group = 23.1). Therefore, for individuals with higher SCI, a greater volume of air would be necessary to be ventilated for the consumption of 100 mL of O_2 for individuals with low SCI and individuals without SCI. Concerning individuals with low SCI, this same analysis is reproduced about individuals without SCI.

Another observation that corroborates the lower cardiorespiratory capacity of the QUADRI group concerning the other groups is the percentage of peak VO_2 at which the COP was reached. Even with reference values for cycle ergometers other than the one for upper limbs, the literature indicates that the COP is reached, on average, between 30 and 50% of $VO_{2max/peak}$ [8]. The referred group reached the COP with about 85% of the peak VO_2 (median value), that is, closer to the highest value of O_2 consumed during the test. This may suggest that after reaching the greatest ventilatory economy, there was not a very expressive increase in VO_2 until the end of the test.

VT1, which represents the beginning of the transition from the predominance of aerobic to anaerobic metabolism, was another submaximal measure in which individuals with SCI presented lower performance than those without SCI. The earlier reaching of this point may be associated with the same factors discussed above; lower muscle mass in the upper limbs, a motor gesture performed in the test different from the one usually used in day-to-day wheelchair propulsion, and changes in cardiac autonomic control. It is noteworthy that, even if individuals with SCI have reached VT1 in higher percentages of VO_{2peak} compared to individuals without SCI, this does not reflect better cardiorespiratory fitness since the VO_{2peak} of these individuals was, in general, low.

A proposal to analyze the aforementioned variables was recently carried out by Costa *et al.* [22] in patients with functional limitation due to unilateral lower limb amputation, a condition that causes mobility impairment and less tendency to exercise, as seen in SCI. In the individuals tested when compared with individuals without amputation, it was also verified lower values of VO_{2peak} for the same intensity of effort; and the COP reached higher percentages of VO_{2peak}. The lower cardiovascular performance of individuals with amputations, similarly to the results of the present study, suggests that mobility limitations, associated with the daily difficulties they impose, may constitute a risk factor for lower cardiovascular capacity.

The present study has as a limitation the performance of CPET on a cycle ergometer for upper limbs and not on a treadmill adapted for a wheelchair in the case of individuals with SCI. Thus, the daily motor gesture could be reproduced, reflecting more accurately the cardiorespiratory capacity of these subjects. However, this is still an unprecedented investigation in this population, which may benefit from the prescription of physical exercises and rehabilitation more specifically indicated for targeted functional gains. There is also the understanding that the analyzed sample belongs to a minority of patients with SCI, considering that a large part of these individuals does not have access to the regular practice of adapted exercises. In future studies, it is suggested to approach sedentary participants, especially considering the significant prevalence of individuals with SCI and the increased cardiovascular risk in this population, and thus contribute to more concretely establishing this risk and individualizing approaches to minimize it.

Conclusion

Individuals with SCI have lower cardiorespiratory fitness at peak and submaximal exertion intensities when compared to individuals without SCI. Concerning COP, the higher the level of SCI, the greater the ventilatory need to meet the metabolic demands of exercise.

Conflict of interest
No potential conflicts of interest relevant to this article have been reported.

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Authors' contributions
Research conception and design: Freitas JP, Vigário PS, Mainenti MRM; **Data collection:** Freitas JP; **Data analysis and interpretation:** Freitas JP, Vigário PS, Mainenti MRM; **Statistical analysis:** Vigário PS, Mainenti MRM; **Obtaining financing:** Vigário PS; **Writing of the manuscript:** Freitas JP, Vigário PS, Mainenti MRM; **Critical review of the manuscript for important intellectual content:** Silva CB.

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