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Key words

- respiratory muscles
- endurance
- exercise performance
- dyspnoea
- spinal cord injury

Abstract

▼ The effect of respiratory muscle endurance training (RMET) on RM function, dyspnoea and exercise performance was evaluated in SCI athletes. Nine endurance athletes (7 paraplegics T4-L1, 2 post-polio syndromes) were evaluated on three occasions (T1–T3), with a 1-month interval between evaluations. Participants performed between T1 and T2 their standard individual exercise training program (control), and between T2 and T3 the same program with 5 additional RMET sessions per week. Each evaluation included: lung function tests, RM strength and endurance tests, a maximal incremental arm cranking test and a field test (simulated competition). Ventilation and dyspnoea were evaluated

during each exercise test. Lung function variables and maximal inspiratory strength were not modified ($p > 0.05$) while maximal expiratory strength ($+23 \pm 36 \text{ cmH}_2\text{O}$; $p < 0.01$) and respiratory endurance ($+3 \text{ min } 33 \text{ s} \pm 2 \text{ min } 42 \text{ s}$, $p < 0.01$) increased from T2 to T3. During the arm cranking test, exercise duration and maximal power output were slightly increased at T3 compared to T2 ($+46 \pm 39 \text{ s}$, $p = 0.09$ and $+8 \pm 8 \text{ W}$, $p = 0.08$) while ventilation and dyspnoea remained similar. During the field test, exercise time ($-10 \pm 33 \text{ s}$, $p = 0.37$) and ventilation were unchanged but dyspnoea was reduced ($-2 \pm 2 \text{ pts}$, $p = 0.02$) between T2 and T3. We concluded that RMET can improve RM function, reduce the perception of dyspnoea but modifies only slightly exercise performance in SCI athletes.

Introduction

▼ Spinal cord injury (SCI) can have a critical impact on the respiratory system by causing respiratory muscle impairment, reduced vital capacity, ineffective cough, reduction in lung and chest wall compliance, increased dyspnoea and excess cost of breathing [4]. Among the different potential interventions aiming to improve the respiratory function in SCI patients, respiratory muscle training may be an interesting option. Inspiratory muscle resistive training (IMT) and respiratory muscle endurance training (RMET) have been shown indeed to improve respiratory muscle performance in healthy subjects, increasing strength and/or endurance depending on training modalities [9]. Several studies evaluated the effect of respiratory muscle training in SCI patients, mainly by using IMT [7, 10, 15]. In a recent meta-analysis, Van Houtte et al. [21] concluded that Respiratory muscle training tended to improve expiratory muscle strength, vital capacity and residual volume in subjects with

SCI, while no definitive conclusions could be drawn regarding changes in inspiratory muscle strength and respiratory muscle endurance. RMET, consisting in isocapnic hyperpnoea training both inspiratory and expiratory muscles, may be an efficient training regimen according to a recent study from Van Houtte et al. [22] showing an improvement in inspiratory and expiratory muscle strength and endurance after 8 weeks of training in SCI patients.

In addition to improving respiratory muscle performance, IMT and RMET have also been shown to increase exercise performance in healthy subjects [3, 17]. Such an increase in exercise endurance may be of relevance for effort tolerance in every day life of sedentary or deconditioned subjects, but may also be viewed as a mean to increase performance in athletes. Very few studies have evaluated the effect of respiratory muscle training on exercise performance in SCI patients. In sedentary SCI subjects, Uijl et al. [20] found that peak oxygen consumption during an incremental maximal arm-cranking exercise test

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was improved by 11% following 6 weeks of an inspiratory flow endurance training. In a recent study in wheelchair racing athletes, Mueller et al. [12] reported a significant reduction in exercise time on a 10-km wheelchair racing time-trial after 30 sessions of RMET, although this improvement did not differ from the change observed in the control group. Therefore, the effect of respiratory muscle training on exercise performances in SCI subjects as well as on potential mechanisms of exercise limitation such as perception of dyspnoea [4,26] needs to be further studied.

Hence, in the present study, we aimed to investigate the effect of RMET on the respiratory function and exercise performance in endurance athletes with SCI. Because of the inability to recruit numerous top-level athletes, we evaluated a group of only nine international athletes before and after 1 month of standard training as well as after the following month combining RMET to standard training. We hypothesized that the addition of RMET to standard training would i) increase respiratory muscle strength and endurance, and ii) improve exercise performance.

Material and Methods

Subjects

Nine spinal cord injured endurance athletes (6 Nordic skiers and 3 wheelchair athletes) of international level participated in the study. Three of them were Olympic or world championship medallists and all have been medallists during their respective national championships. Participants were requested to keep their individual training constant (same duration, intensity and type of training) for at least two weeks before and throughout the course of the study. The study was performed during the main training period of the athletes, two to four months before their main competition period. All training details, including respiratory training (see below), were recorded in a diary and checked by the experimenter. Weekly amount of training during the protocol period is provided in **Table 1**. Participants refrained from intense physical activity two days before the tests and from any physical exercise the day before the tests. Participants gave their written informed consent to participate in the study that was approved by the local ethics committee (Grenoble University Hospital).

Protocol

All participants reported to the laboratory on three occasions with a one-month training period separating each testing day. The three testing days included the following evaluations, always performed in the same order and at the same time of the day: lung function measurements, a maximal incremental arm cranking test, respiratory muscle strength and endurance measurements (1 h after the arm cranking test) and a field exercise test simulating an actual competition (5 h after the arm cranking test). Between the first (T1) and the second (T2) testing days, participants had to follow their individual training program without RMET, i.e., the control period. Between the second and third (T3) testing days, participants had to keep the same training program and to perform five additional RMET sessions per week, i.e., the experimental period. T3 was carried out 72 h after the last RMET session.

Respiratory muscle endurance training

Between T2 and T3, all participants had to perform 20 RMET sessions of 30 min duration, with one day of rest between two days of consecutive training. RMET was performed as previously described [25] with a commercially available respiratory endurance training device (SpiroTiger[®], Idiag, Fehraltorf, Switzerland) allowing partial rebreathing of CO₂ and thus assuring normocapnic hyperpnoea. RMET consisted of voluntary normocapnic hyperpnoea at a given tidal volume (V_T) and breathing frequency (f_R) with a duty cycle of 0.5. The SpiroTiger[®] provided breath-by-breath feedback of f_R and V_T . The size of the rebreathing bag was set at 50–60% of vital capacity, and minute ventilation (\dot{V}_E) of the first training session was set at 60% of maximal voluntary ventilation (MVV). Participants were instructed to increase f_R from one session to another as we described previously [25]. Training settings were recorded in a diary and all participants were phone called at least once per week by the experimenter in order to verify compliance.

Measurements

Lung function and ventilatory measurements

Lung function as well as ventilation, gas exchange and heart rate (HR) during the respiratory endurance test and all exercise tests were measured with a portable ergospirometric device (Oxycon Mobile; Jaeger, Höchberg, Germany) calibrated before each test. Maximal inspiratory (MIP) and expiratory (MEP) mouth pressure were measured at residual volume and total lung capacity,

Table 1 Subject characteristics.

Subject	Height (cm)	Weight (kg)	Age (yrs)	Lesion level	Lesion duration (yrs)	Sport	Sport category	Training (h · week ⁻¹)
1	174	71	44	Polyo (at 3 months)	–	Nordic	LW11.5	18
2	175	67	49	T12-L1	4	Nordic	LW11	6
3	177	57	39	L1	23	Wheelchair	T54	10
4	176	65	39	T4–5	15	Wheelchair	T53	10
5	191	70	45	T10–11	5	Nordic	LW10.5	10
6	173	65	37	T7–8	4	Nordic	LW10	12
7	175	76	46	T10–12	22	Nordic	LW11	12
8	178	55	31	T11	7	Nordic	LW11	6
9	169	54	42	Polyo (at 1.5 yrs)	–	Wheelchair	T54	7
Mean	176.4	64.4	41.3	–	11.4	–	–	10.1
SD	6	7.7	5.5	–	8.5	–	–	3.8

Polyo, subjects with post-poliomyelitis syndrome (age of poliomyelitis); Nordic, Nordic skier; Wheelchair, wheelchair athlete; Training, weekly amount of training during the protocol period

Table 2 Subject lung function and respiratory muscle strength at T1.

Subject	VC (% pred)	FVC (% pred)	FEV ₁ (% pred)	FEV ₁ /FVC (% pred)	PEF (% pred)	FEF ₂₅₋₇₅ (% pred)	MVV (% pred)	MIP (% pred)	MEP (% pred)
1	141.9	142.5	122.8	85.9	103.9	69.6	130.4	91	155
2	95.7	99.6	97.2	100.6	88.2	81.2	91.4	71	96
3	84.6	88.2	91.5	106.6	74.6	96.2	127.9	127	101
4	83.2	86.4	88.6	105.0	103.2	81.1	111.5	170	124
5	105.5	103.6	98.7	91.0	90.2	69.8	111.6	136	166
6	95.3	97.4	83.8	86.9	54.4	54.4	94.9	108	81
7	83.1	83.0	87.3	104.0	79.4	85.7	119.2	151	167
8	84.2	88.1	87.4	101.5	85.5	82.9	102.4	83	89
9	138.2	144.0	135.1	97.6	115.4	98.1	157.4	119	164
Mean	101.3	103.6	99.2	97.7	88.3	79.9	116.3	117.3	127.0
SD	23.2	23.4	17.8	7.9	18.1	13.7	20.5	32.5	36.2

VC, vital capacity; FVC, forced vital capacity; FEV₁, forced expiratory volume in 1 s; PEF, peak expiratory flow; FEF₂₅₋₇₅, forced expiratory flow between 25 and 75% of FVC; MVV, maximum voluntary ventilation; MIP, maximum inspiratory pressure; MEP, maximum expiratory pressure; % pred, percentage of predicted values

respectively (BodyBox 5500, Medisoft, Dinant, Belgium). Lung function, MIP and MEP were measured according to standard recommendations [1, 11].

Respiratory endurance test

The test was performed with the SpiroTiger® device connected to the ergospirometric device. The test consisted in an incremental protocol according to recommendations from ATS/ERS [1]. The size of the rebreathing bag was set at 40–50% of vital capacity, and the target \dot{V}_E for the first 3 min was 20% MVV. Then, \dot{V}_E was increased by 10% MVV every 3 min until the subject could not maintain the target f_R and V_T . The total test duration as well as the maximum ventilatory level sustained for at least 3 min were recorded.

Maximal incremental arm cranking test

The test was performed on an electronically-braked asynchronous arm ergometer starting at 30 W. Every min, the load was increased by 10 or 15 W (depending on the subject's maximal power output previously measured) until voluntary exhaustion or inability to maintain the target cranking frequency (90 rpm). Every 2 min, participants were asked to perform a maximal inspiratory manoeuvre from end expiratory lung volume in order to measure inspiratory capacity (IC) and to assess the operational lung volume [13]. Participants were familiarized with this manoeuvre at rest and the better of two measurements was recorded at each time point during exercise. Every 2 min and at maximum exercise, 20 μ l arterialized capillary blood were drawn from an earlobe and analyzed (SGI Microzym-L, Toulouse, France) to determine blood lactate concentration ([La]). At rest as well as during the last 30 s of exercise, arterial blood gas and pH were assessed by an immediate analysis of a 125 μ l arterialized blood sample from the earlobe (AVL instruments, Graz, Austria) [24]. Immediately after the end of exercise, participants were asked to rate i) their maximum perception of dyspnoea on a visual analogue scale consisting of a 10-cm long line labelled with 'none' on the right-hand side and 'maximal' on the left-hand side with a cursor being moved by the participants between both extremities, and ii) over 100%, the percentage of limitation due to arm fatigue and due to dyspnoea at maximum exercise.

Field exercise test

Participants performed the three field tests in their own racing wheelchair or roller ski chair and under similar stable meteorological conditions [no rain and similar weather conditions (tem-

perature, sun and wind were rated from 0 to 5 on each experimental session)]. The test was performed on a straight, flat (for wheelchair athletes) or steep (4% slope on average, for Nordic skiers) tarred road 4 to 9 km long. The road profile and distance were chosen in order to reproduce specific racing conditions and to provide similar exercise duration for all participants. After a 15 min standardized warm-up, participants had to complete the test distance as fast as possible. Participants performed the test individually. Immediately after the end of exercise, participants rated their perception of dyspnoea as described above.

Statistical analysis

An analysis of variance (ANOVA) with repeated measures was used to assess changes in lung function, respiratory muscle performance and exercise response over the protocol period (T1–T3). If significance was found, Fisher's protected least-significant difference post-hoc analysis was applied to locate the difference. All statistical evaluations were performed using standard statistical software (Statview 5.0; SAS Institute, Cary, North Carolina, USA). All data are presented as means \pm SD and $p < 0.05$ was considered statistically significant.

Results



Subject characteristics and lung function are shown in **Tables 1, 2**. Analysis of training diary indicated that the individual duration, intensity and type of training during the protocol period remained similar. Compliance to the RMET program was excellent since all participants performed the 20 RMET sessions as recorded in the diaries.

Lung function

No significant change in lung function was observed throughout the protocol period (**Table 3**).

Respiratory muscle strength

MIP did not change throughout the protocol period while MEP increased at T3 compared to T1 and T2 (**Fig. 1**).

Respiratory endurance test

Breathing duration was increased at T3 compared to T1 and T2 (**Fig. 1**). $\dot{V}_{E\max}$ and $f_{R\max}$ were also increased at T3 compared to T1 and T2, while $V_{T\max}$ remained similar throughout

Table 3 Lung function and maximal ventilation during the respiratory endurance test during the protocol period.

Test session	VC (l)	FVC (l)	FEV1 (l)	FEV1/FVC (%)	PEF (l·s ⁻¹)	FEF25–75 (l·s ⁻¹)	MVV (l·min ⁻¹)	$\dot{V}_{E\max}$ (l·min ⁻¹)	$f_{R\max}$ (min ⁻¹)	$V_{T\max}$ (l)
T1	5.00 (1.00)	4.90 (0.97)	3.85 (0.59)	79.4 (5.8)	8.12 (1.60)	3.47 (0.61)	161.2 (25.5)	119.1 (16.3)	48.4 (6.6)	2.51 (0.37)
T2	5.16 (0.98)	4.87 (0.89)	3.80 (0.58)	78.4 (5.2)	7.93 (1.74)	2.96 (0.70)	165.2 (27.9)	117.5 (21.7)	45.7 (7.9)	2.59 (0.32)
T3	5.12 (0.89)	4.95 (0.89)	3.84 (0.47)	78.5 (6.8)	7.92 (0.86)	3.32 (0.76)	170.7 (21.5)	132.3* (18.6)	52.4* (6.8)	2.55 (0.44)

Values are Mean (SD); T1, first testing session; T2, second testing session; T3, third testing session; $\dot{V}_{E\max}$, maximal minute ventilation during the respiratory endurance test; $f_{R\max}$, maximal breathing frequency during the respiratory endurance test; $V_{T\max}$, maximal tidal volume during the respiratory endurance test; see **Table 2** for abbreviations. * different from T1 and T2 ($p < 0.05$)

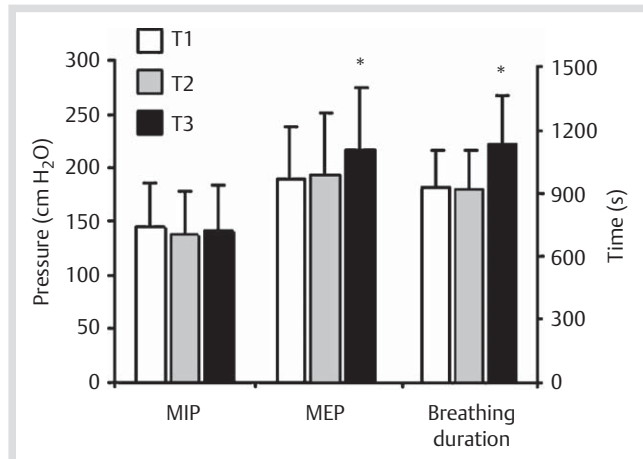


Fig. 1 Maximal inspiratory (MIP) and expiratory (MEP) pressures and duration of the respiratory endurance test on the first (T1), second (T2) and third (T3) testing session. * different from T1 and T2 ($p < 0.05$).

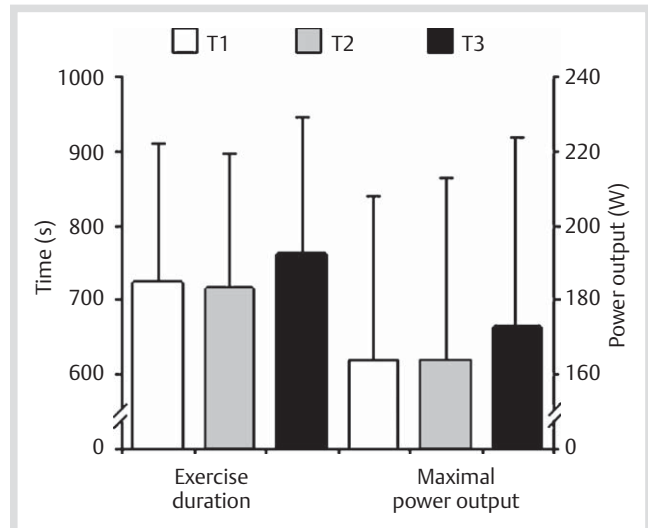


Fig. 2 Exercise duration and maximal power output during the maximal incremental arm cranking test on the first (T1), second (T2) and third (T3) testing session.

the protocol (i.e., in accordance with the SpiroTiger settings) (**Table 3**). Averaged isotime HR during the respiratory endurance test was significantly reduced at T3 compared to T1 and T2 (T1 99.1 ± 10.2 vs. T2 98.2 ± 11.0 vs. T3 91.3 ± 11.4 bpm; $F = 4.438$, $p = 0.029$).

Maximal incremental arm cranking test

Although exercise duration and maximal power output were not significantly higher at T3 compared to T1 and T2 (exercise duration $F = 2.823$, $p = 0.089$; maximal power output $F = 3.030$, $p = 0.077$; **Fig. 2**), the effect size for changes between T1 and T2 vs. changes between T2 and T3 were high (exercise duration 0.80; maximal power output 0.74). No significant difference in cardio-respiratory variables at maximal exercise was observed throughout the protocol period (**Table 4**). Subject 4 only had exercise-induced hypoxemia (i.e., a reduction in $\text{PaO}_2 > 12$ mmHg or in $\text{SaO}_2 > 4\%$ from rest to maximal exercise; [6]) and subject 5 only had a reduction in IC at maximal exercise compared to resting value (i.e., dynamic hyperinflation; [13]), both observations remaining similar throughout the protocol period.

Field exercise test

The time needed to complete the test distance did not differ between T1, T2 and T3 (effect size 0.06) as well as mean cardio-respiratory variables during the test (**Table 5**). Perceived level of dyspnoea only (both expressed as absolute value on the visual analog scale and as a percentage of global exercise limitation) was significantly reduced at T3 compared to T1 and T2 (**Table 5**).

Discussion

The results showed that a 1-month RMET program in SCI top-level endurance athletes increased expiratory muscle strength and respiratory endurance without significant effect on inspiratory muscle strength and lung function variables. In addition, RMET did not increase significantly exercise duration and maximal power output during the maximal incremental arm cranking test despite values slightly higher following RMET. During the field exercise test, reproducing specific racing conditions, RMET did not modify performance but significantly reduced the perception of dyspnoea.

Training effects

Lung function

While previous reports in sedentary SCI patients showed an improvement in vital capacity and residual volume after respiratory muscle training (for a review see [21]), no change in lung function was observed in the present study. As shown in **Table 2**, participants had already normal lung function at the start of the protocol. This may be the consequence of both the lesion level and the training status of the athletes. The impairment of lung function in SCI patients is indeed dependent on the lesion level [14] and patients with the lowest lesion often exhibit lung function comparable to the able-bodied population [2,8]. The French national wheelchair racing and Nordic skiing teams being mainly composed of SCI athletes with low level of injury, the participants of the present study had probably little impairment of lung function because of their injury. The small preva-

Table 4 Cardio-respiratory variables at maximal exercise during the incremental arm cranking test.

Test session	$\dot{V}O_2$ ($l \cdot min^{-1}$)	$\dot{V}CO_2$ ($l \cdot min^{-1}$)	RER	PET CO_2 (mmHg)	$\dot{V}E$ ($l \cdot min^{-1}$)	f_R (cycles $\cdot min^{-1}$)	V_T (l)	IC (l)	HR (bpm)	La (mmol $\cdot l^{-1}$)	PaO ₂ (kPa)	SaO ₂ (%)	PaCO ₂ (kPa)	pH	Dyspnoea (points)	Dyspnoea (%)
T1	2.44 (0.49)	2.83 (0.50)	1.18 (0.07)	28.7 (5.6)	115.3 (31.4)	50.7 (10.2)	2.31 (0.49)	3.31 (0.49)	176.9 (12)	10.4 (2.2)	11.4 (1.7)	94.8 (2.8)	4.0 (0.8)	7.39 (0.04)	6.7 (0.9)	34.4 (14.2)
T2	2.47 (0.43)	2.83 (0.42)	1.15 (0.05)	29.3 (4.7)	115.0 (33)	49.8 (13.3)	2.38 (0.51)	3.18 (0.66)	175.6 (11.3)	11.0 (1.9)	11.8 (2.1)	94.8 (3.4)	4.1 (0.6)	7.38 (0.05)	5.9 (2.1)	33.3 (11.5)
T3	2.41 (0.48)	2.81 (0.52)	1.17 (0.09)	28.5 (4.8)	115.0 (31.3)	52.3 (14.3)	2.29 (0.48)	3.38 (0.78)	177.0 (13.6)	10.6 (2.5)	11.6 (1.7)	95.9 (2.7)	3.8 (0.6)	7.39 (0.03)	6.3 (2.5)	26.7 (13.2)

Values are Mean (SD); $\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide production; RER, respiratory exchange ratio; PET CO_2 , end-tidal CO₂ partial pressure; $\dot{V}E$, minute ventilation; f_R , breathing frequency; V_T , tidal volume; IC, inspiratory capacity; HR, heart rate; La, blood lactate concentration; PaO₂, arterial oxygen partial pressure; PaCO₂, arterial carbon dioxide partial pressure; Dyspnoea, level of perceived dyspnoea quoted on a visual analog scale or as a percentage of global exercise limitation; see **Table 3** for abbreviations

Table 5 Duration and mean cardio-respiratory variables during the field exercise test.

Test session	Time (min - s)	$\dot{V}O_2$ ($l \cdot min^{-1}$)	$\dot{V}CO_2$ ($l \cdot min^{-1}$)	RER	PET CO_2 (mmHg)	$\dot{V}E$ ($l \cdot min^{-1}$)	f_R (min^{-1})	V_T (l)	HR (bpm)	Dyspnoea (points)	Dyspnoea (%)
T1	20min 19 s (2 min 1 s)	2.17 (0.38)	2.21 (0.43)	1.02 (0.07)	24.1 (2)	117.9 (18.1)	65.6 (13.9)	1.91 (0.49)	170.0 (9.8)	8.1 (1.3)	55.0 (20.9)
T2	20min 7 s (2 min 3 s)	2.31 (0.44)	2.33 (0.45)	1.01 (0.06)	25.0 (2.9)	118.1 (25.9)	62.3 (16.4)	2.04 (0.56)	167.9 (20.9)	8.4 (0.8)	52.2 (25.3)
T3	19min 57 s (2 min 19 s)	2.25 (0.39)	2.32 (0.45)	1.03 (0.04)	24.8 (2.9)	119.5 (25.8)	65.8 (16.6)	1.95 (0.46)	170.8 (11.5)	6.8* (2.2)	41.1* (16.9)

Values are Mean (SD); Time, duration of the field exercise test; see **Table 4** for abbreviations. *different from T1 and T2 (p<0.05)

lence of exercise-induced hypoxemia as well as lung hyperinflation during intense exercise confirmed that our subjects did not present major lung function impairment. Moreover, Silva et al. [18] showed in sedentary SCI subjects that a 6-week upper body exercise (arm cranking) training program increased FVC and respiratory muscle endurance. Therefore, SCI athletes may have already improved or normalized lung function because of their high level of upper body training, and thus they may show reduced response to additional specific respiratory muscle training.

Respiratory muscle function

In able-bodied subjects, RMET increases respiratory muscle endurance without significant effect on respiratory muscle strength [9]. In patients with impaired respiratory muscle function however, RMET can also increase MIP and/or MEP [16,22]. The increase in MEP in the present study emphasized the positive effect of RMET on respiratory muscle function in SCI patients, these effects being observed even in SCI athletes with low lesion level, long injury duration and high training status. Interestingly, mean HR during the respiratory endurance test was reduced following RMET. Recent observations in able-bodied subjects [27] suggested that IMT may attenuate the sympathetically-mediated metaboreflex induced by respiratory muscle fatigue [5]. Hence, the present results suggest that RMET may also prevent cardiovascular changes associated with increased work of breathing and respiratory muscle fatigue in SCI patients.

Exercise performance

Both IMT and RMET have been shown to improve exercise performance in able-bodied subjects [3,17], although not systematically [19]. An increase in respiratory muscle fatigue-resistance [25] and/or an improvement in respiratory sensations [23] may be responsible for such an improvement. To our knowledge, only one study investigated the effect of respiratory muscle training in sedentary SCI patients [20] and reported a significant improvement in peak aerobic performance. In SCI athletes however, because intense upper body exercise training may have already enhanced respiratory muscle performance [18], adding RMET to the standard training regimen might not be able to provide significant additional improvement in exercise performance [12]. In the present study, two exercise tests were used to evaluate the effect of training in SCI athletes, and only one was specific to the training and racing movement performed by the athletes. Although no significant training effect was observed for both types of exercise test, slightly higher exercise duration and maximal power output during the maximal incremental arm cranking test at T3 compared to T1 and T2 (p<0.01) as well as high effect size (0.80 and 0.74) suggested that the addition of RMET to standard training can improve maximal arm cranking performances. Interestingly, this slight effect was observed during the arm cranking test only, i.e., during the non-specific test, while no improvement was shown during the field test reproducing specific training and racing conditions. Therefore, it may be hypothesized that RMET could improve performance during arm cranking because the athletes were less adapted to this type of exercise and therefore additional training of respiratory muscles may have improved both breathing and movement efficiency. During the field test however, the high level of muscular adaptation of the athletes to their specific sport task may provide little room for additional improvements in performance following the addition of RMET to standard training.

Dyspnoea

Because of impairment of respiratory muscle and chest wall mechanics, the prevalence of dyspnoea can be increased in SCI patients [4,26]. Since RMET can improve respiratory sensations in healthy subjects [23], it may be an effective intervention to alleviate dyspnoea in SCI patients. To our knowledge, only two studies evaluated the effect of IMT on respiratory sensations in SCI patients, showing non significant [15] or significant [10] reduction in dyspnoea. In the present study, RMET significantly reduced the perception of dyspnoea during the field test together with unchanged performances, while during the arm cranking test dyspnoea was similar despite an increase in maximal power output. On the one hand, these results indicate that RMET reduces the perception of dyspnoea, even in athletes with low lesion level and high training status, and that it should be considered as an attractive intervention to improve respiratory sensations in SCI patients with increased prevalence of dyspnoea [4,26]. On the other hand, these results suggest that dyspnoea does not represent a major exercise limiting factor in SCI athletes. Whether this is also the case in sedentary SCI subjects remains however to be investigated.

Limitations of the study

Few SCI top-level endurance athletes with spinal cord injury are available and this had three main consequences for our study. First, it was not possible to make a true controlled study, i.e., with two arms including sufficient amount of subjects. This is critical for studies evaluating the effect of interventions like respiratory muscle training [19]. However, to be able to compare the effects of RMET to the effects of a standard training program (considered as the control condition), participants were evaluated three times over a 2-months period of constant standard training, except the addition of RMET during the second month. We believe therefore that despite the absence of a true control group we were able to evaluate the independent effect of RMET compared to the athletes' standard training program. RMET was performed for all participants during the second month and not randomly the first or the second month because in the former case the comparison of T2 and T3 would have been influenced by standard training but also by detraining of the respiratory muscle. Secondly, the sample size being quite small, it increased the risk of type 2 error. When performing the statistical analysis with double sample size, the slight but non significant changes mentioned in the results section (i.e., ANOVA time-effect: $p < 0.09$) became clearly significant, with increased exercise duration and maximal power output during the incremental arm cranking test at T3 compared to T1 and T2 (all $p < 0.01$). Hence, it suggests that these changes represented a true effect of RMET on maximal arm cranking performances as confirmed by the high effect sizes. Thirdly, both Nordic and wheelchair athletes were recruited and evaluated together. Most of the evaluations were standardized laboratory tests and the duration of the field test was similar for Nordic and wheelchair athletes. Moreover, changes from T1 to T3 were similar in Nordic and wheelchair athletes (results not shown). Therefore, we believe that evaluating Nordic and wheelchair athletes together did not introduce bias in the present study.

In conclusion, the present study showed that the addition of RMET to standard training in endurance athletes increased expiratory muscle strength and respiratory muscle endurance, reduced the perception of dyspnoea during exercise and slightly increased exercise performance during non racing-specific exer-

cise. The lesion level as well as the training status probably influenced the impact of RMET in SCI subjects. These results indicate that RMET should be considered as an attractive intervention to improve respiratory muscle function, respiratory sensations and exercise performance in SCI patients.

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