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ORIGINAL ARTICLE

Energetic and cardiovascular responses to treadmill walking and stationary cycling in subjects with incomplete spinal cord injury

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Study design: Randomized controlled trail.
Objectives: To investigate if people with incomplete spinal cord injury (SCI) can perform high-intensity weight-bearing exercise by comparing cardiovascular responses at maximal workloads during stationary cycling and treadmill walking, and to explore mechanical efficiencies at sub-maximal workloads.
Setting: Sunnaas Rehabilitation Hospital, Nesoddtangen, Norway.
Methods: Fifteen people with incomplete SCI and 15 healthy control subjects performed sub-maximal and maximal exercise tests of both stationary cycling and uphill treadmill walking on separate days. Oxygen uptake (VO_2; $l\,min^{-1}$ and $ml\,kg^{-1}\,min^{-1}$), carbon dioxide production (VCO_2; $l\,min^{-1}$), respiratory exchange ratio (RER) and heart rate (HR) were continuously measured throughout the tests.
Results: The SCI group showed no significant differences in peak VO_2 ($2.42 \pm 0.68\,l\,min^{-1}$ versus $2.58 \pm 0.76\,l\,min^{-1}$, $P = 0.19$) or other cardiovascular responses at maximal workloads for stationary cycling as compared with uphill treadmill walking, except for higher RER during the cycle test. The control subjects exhibited a significantly higher peak VO_2 during the treadmill test as compared with the cycle test ($P = 0.007$). Both groups had lower mechanical efficiency when walking as compared with cycling, but the mean difference between cycling and walking was not significantly different between the groups during sub-maximal workloads ($P > 0.24$).
Conclusion: Subjects with incomplete SCI were able to perform high-intensity weight-bearing exercise and exhibited similar mechanical efficiencies at sub-maximal workloads as healthy controls. Uphill walking might be a good alternative to weight-bearing exercise for increasing the physical capacity of people with incomplete SCI.
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INTRODUCTION

The positive health benefits of regular physical exercise are widely recognized.[1,2] However, limited engagement in physical activity is a major independent risk factor and important modifier for cardiovascular diseases.[3] Having a spinal cord injury (SCI) is associated with reduced physical function, and thus reduced physical capacity, and forms the basis for a more sedentary lifestyle and lower energy expenditure levels as compared with able-bodied persons.[4] This increases the risk for secondary health problems. The incidence of overweight, hypertension, diabetes and cardiovascular disease is higher in persons with SCI, compared with healthy persons.[5,6] Thus, for persons with SCI, regular exercise is important to improve or maintain physical capacity and quality of life.[7]

A person's physical capacity can be expressed as their peak oxygen uptake (peak VO_2). As peak VO_2 primarily is dependent on a person's stroke volume, performing exercise at a high intensity (that is, 85–95% of the maximal heart rate) by engaging many large muscle groups seems to be most beneficial to increasing physical capacity.[8] In the able-bodied population, weight-bearing training modes like running and uphill walking are found to be effective in increasing the peak VO_2.[8] The majority of the individuals with SCI also have incomplete neurological lesions[9,10] and thus maintain a level of motor and/or sensory function below their level of injury. Although many people with incomplete SCI have the ability to walk (that is, with or without assistive aids), cycling is still a commonly used exercise mode to increase physical capacity. It is not known, however, if this group might be able to perform high-intensity exercise by using a weight-bearing exercise mode such as uphill walking. Furthermore, in order to provide optimal training recommendations for this group it is necessary to investigate if the energy costs at sub-maximal intensities differs between nonweight-bearing and weight-bearing exercise modes.

The ratio between the energy costs of the work performed and the extra energy costs during the exercise expresses the mechanical efficiency of the exercise. It reflects the percentage of the total energy expended that contributes to external work, where the remainder is lost as heat.[11] A high mechanical efficiency is associated with better results in various sport disciplines. During exercises as walking, running and cycling, the efficiency of locomotion usually ranges between 20 and 30%.[11]The mechanical efficiency is generally higher in nonweight-bearing activities like cycling as compared with running.[12] Walking and running demand balance and coordination in order to economize energy expenditure. Owing to their difficulties with balance and coordination, it is expected that persons with incomplete SCI have lower mechanical efficiency during walking as compared with

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stationary cycling. Thus, we hypothesized that people with incomplete SCI have a larger difference in mechanical efficiency between stationary cycling and treadmill walking than able-bodied persons.

This study explores if people with incomplete SCI are able to perform high-intensity weight-bearing exercise by comparing cardiovascular responses at maximal workloads during stationary cycling and treadmill walking. This study also investigates the mechanical efficiencies of people with incomplete SCI at two sub-maximal workloads during both exercise modes and compares those results with those of a healthy control group.

MATERIALS AND METHODS

Participants

Fifteen subjects with incomplete SCI (SCI group) and 15 healthy subjects (control group) were included in the study. Subjects in the SCI group were recruited during inpatient care at Sunnaas Rehabilitation Hospital. They were eligible if they had a traumatic or nontraumatic and classified, according to the American Spinal Injury Association (ASIA) Impairment Scale (AIS), as AIS D.[13] They also had to be able to walk for 5 min on the treadmill at a speed of 4 km h^{-1} (that is, with no incline). Subjects were excluded if they were unable to walk without the use of assistive walking aids or if they had a cardiovascular disease. The level of injury ranged from cervical-3 (C_3) to lumbar-5 (L_5). Eight people suffered a cervical injury, one had a high thoracic lesion ($TH_{1\text{-}6}$), three had a low-thoracic lesion ($TH_{6\text{-}12}$), and three had a lumbar injury level. The time since injury ranged from 4 months to 14 years.

The control group consisted of healthy able-bodied volunteers who were employed at Sunnaas Rehabilitation Hospital. The age, body weight and body mass index (BMI) of the control group was not significantly different from the SCI group (Table 1).

The study was approved by the Regional Committee for Medical and Health Research Ethics. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research. All subjects were informed of the purpose, procedures, and potential risks of the study with written and verbal communications before they signed informed consent documents. Before taking part in the exercise tests, the SCI subjects needed permission from a medical doctor.

Procedures

All subjects performed two incremental exercise tests until exhaustion, one on a treadmill and one on a stationary cycle. Exercise tests were performed at the same time of day and on two separate days; the repeat tests were conducted between 2 and 5 days apart. Half the subjects started with the stationary cycle exercise, whereas the other half started with the treadmill exercise. The sequence order was randomized by drawing lots. For practical reasons, blinding of participants and staff was not possible.

Before starting the exercise tests the subjects sat quietly for 15 min to determine their resting energy expenditure (REE), followed by a 10-min standardized warm up and 3 min recovery. Subjects then performed the sub-maximal exercise tests at, respectively, 30 and 60 watts, both lasting 5 min. Between and after the sub-maximal workloads the subjects rested for 5 min. Then subjects performed a maximal exercise test, using a continuous stepwise protocol in which the workload increased every 3 min until exhaustion. As none of the participants had experienced spontaneously occurring autonomic dysreflexia, standard indications for terminating the exercise tests were used; exhaustion, a systolic blood pressure (BP) exceeding 280 mm Hg, or a >10% decrease in systolic BP as compared with resting systolic BP. All tests were performed at room temperature (that is, between 20 and 22°C). All subjects were asked to refrain from alcohol, exercise, or strenuous physical activity within 24 h of the exercise tests. They were also asked not to smoke, drink coffee, or eat in the hour preceding the tests.

Table 1 Participant characteristics

	SCI group (n = 15) mean (s.d.)	Control group (n = 15) mean (s.d.)	P-value
Age (years)	40 (11.9)	42 (9.2)	0.72
Weight (kg)	81 (15.1)	78 (13.2)	0.75
BMI (kg m^{-2})	25.1 (4.1)	24.1 (2.6)	0.52
Male:female ratio	12:3	10:5	—

Abbreviations: BMI, body mass index; SCI, spinal cord injury.

Cycle exercise test

The stationary cycle exercise test was performed on a cycle ergometer (ER 800, Erich Jaeger, Germany). The warming up was performed at a work load of 40 watts with a speed of 60 revolutions per min (r.p.m.). The sub-maximal exercise test was standardised at 30 watts followed by 60 watts, both at 60 r.p.m.

Treadmill walking exercise test

The walking exercise test was done on a treadmill (Sportsmaster T300, Sportsmaster, Nesbru, Norway). Warm up was set at a speed of 4 km h^{-1} with zero incline. The sub-maximal exercise test was standardized so that subjects walked at an incline and speed that was equivalent to cycling at 30 and 60 watts, respectively, determined by the following equation:

$$\text{Speed}(km/h^{-1}) = \frac{\text{watt}}{([\text{mb} \times \text{N}] \times \text{Sin}\,\theta)} \times 3.6 \quad (1)$$

where m_b, N and Sinθ are body mass in kg, force of gravity and elevation on the treadmill, and the sine of the angle of elevation on the treadmill, respectively.[11] The elevation used in the calculation was set at five or seven percent.

The maximal exercise test had a starting workload set at a speed of 4 km h^{-1} with 5% incline, and was intensified by increasing the incline by 5% every 3 min. After the subject reached 3 min at 15% incline, treadmill speed was increased by 1 km h^{-1} every 3 min until exhaustion. A safety harness was available during the walking test and a member of the research team was present to press the emergency stop button, if needed.

Cardiovascular measurements

During the exercise tests, VO_2 (l min^{-1} and ml kg^{-1} min^{-1}), carbon dioxide production (VCO_2; l/min), RER and pulmonary ventilation (V_E; l min^{-1}) were continuously measured by a computerized standard open-circuit technique breath-by-breath spirometer (Vmax 220, Sensormedics Corporation, Yorba Linda, CA, USA). Volume and gas calibration was performed prior to each test. Heart rate (HR) and BP were measured with the Tango Automated Blood Pressure Monitor (SunTech Medical, Morrisville, NC, USA). HR was continuously measured during all test stages. During the maximal exercise test, BP was measured during the last minute of every workload in order to assess possible autonomic dysfunction. To quantify anaerobic work, blood lactate concentration ([La$^-$]; mmol l^{-1}) was measured after the sub-maximal workloads using fingertip capillary blood samples, and analyzed with a 1500 YSI sport lactate analyzer (YSI incorporated, Yellow Springs, OH, USA). Due to practical constraints, [La$^-$] was not measured during the maximal exercise tests.

Perceived exertion

Perceived exertion was measured instantly after the maximal exercise test with the Borg Scale (6–20).

Data analyses and statistics

To determine the energy expenditure (Kcal min^{-1}), breath-by-breath data were time-averaged into 1 min intervals and mean VO_2 values were multiplied by the caloric equivalent associated with the mean RER values (that is, the ratio between VO_2 (l min^{-1}) and CO_2 (l min^{-1})).[11] REE was calculated by multiplying the VO_2 and caloric equivalents, averaged over the last 5 min of the rest period. Energy expenditure during exercise (E) was calculated using the VO_2 and RER values averaged over the second, third and fourth minute during the sub-maximal workloads. When estimating E and REE, a RER value <1.0 is assumed.

Mechanical efficiency was calculated using work accomplished divided by energy expended above resting level according to the following equation:

$$\text{Mechanicalefficiency}(\%) = \frac{\text{watt} \times 0.01433}{(\text{E} - \text{REE})} \times 100 \quad (2)$$

where watt, E and REE are the exercise load, energy expenditure during exercise (Kcal min^{-1}), and resting energy expenditure (Kcal min^{-1}), respectively.[14] The figure 0.01433 represents one caloric equivalent.

During the maximal exercise tests the highest VO_2 achieved (that is, averaged over 1 min) was used as peak VO_2. The highest registered HR was used as peak HR.

Power calculations

Assuming that subjects with incomplete SCI have higher maximal oxygen uptake during running compared with cycling, as shown in healthy nonathletic subjects,[15,16] we needed 16 subjects to detect a mean difference of 0.4 l min^{-1} in peak VO_2 between cycling and treadmill walking. This sample size calculation was based on a s.d. of 0.5 l min^{-1} with significance level of 0.05 and power output of 80%.

Statistics

Statistical analyses were performed using the Statistical Package for the Social Science (release 19.0.0.2 SPSS Inc, Chicago, IL, USA). Mean values $\pm$ 1 s.d. are reported unless otherwise stated. A two-tailed significance level of 5% was adopted.

Independent sample *t*-tests were used to compare the cardiovascular responses at the sub-maximal and maximal exercise workloads between the SCI and control groups, both for the stationary cycling and the treadmill walking exercise modes. To compare the mechanical net efficiency during treadmill walking versus cycling, paired sampled *t*-tests were used.

RESULTS

Due to illness, two control subjects completed the exercise test only on the treadmill and not on the stationary cycle.

Maximal exercise tests

In the SCI group, maximal workload cardiovascular responses showed no significant difference between stationary cycling and uphill treadmill walking, except for a higher RER value during the cycle test (Table 2). None of the participants experienced spontaneously occurring autonomic dysreflexia during the tests. General exhaustion was the reason for termination for all subjects in this study. The perceived exertion was rated somewhat higher during cycling compared with walking (Borg scale; median (min–max); 20 (15–20) versus 18 (13–20), $P = 0.06$). In contrast to the SCI group, the healthy control subjects exhibited a significantly higher peak VO_2 during the treadmill test compared with the cycle test ($P = 0.007$) and a near-significant higher peak HR ($P = 0.059$; Table 2). In the control group, no significant difference in perceived exertion between treadmill walking and cycling was found (Borg scale; median (min–max); 19 (17–20) versus 20 (18–20), $P = 0.73$).

Subjects in the SCI group exhibited a significant lower peak VO_2 and peak HR than those in the control group for maximal workloads on both the cycle and treadmill exercise tests (0.89 ± 0.24 l min^{-1} lower, $P = 0.001$ and 1.08 ± 0.29 l min^{-1}, $P = 0.001$, respectively, for the cycle test; 15 ± 7 beats per min, $P = 0.03$ and 13 ± 6 beats per min lower, $P = 0.04$, respectively, for the treadmill exercise test). However, comparison of the mean differences in peak VO_2 and peak HR at maximal workloads between the two exercise modes (cycling and treadmill walking) revealed no statistically significant differences between the SCI and control groups ($P = 0.16$ and $P = 0.74$, respectively). The mean maximal workload (in watts) during cycling and treadmill walking for the SCI group were 176 ($\pm$56) W and 264 ($\pm$96) W ($P < 0.001$), respectively, versus 264 ($\pm$52) W and 430 ($\pm$101) W ($P < 0.001$), respectively, in the control group.

Table 2 Cardiovascular responses during maximal incremental exercise testing on a stationary cycle versus treadmill (uphill) walking, for both SCI ($n = 15$) and control group ($n = 13$)

	Group	*Stationary cycling*	*Treadmill walking*	*P-value*
Peak VO_2(l min^{-1})	*SCI*	2.42 ($\pm$0.68)	2.58 ($\pm$0.76)	0.188
	Control	3.31 ($\pm$0.58)	3.71 ($\pm$0.88)	0.007[a]
Peak VO_2(ml kg min^{-1})	*SCI*	30.62 ($\pm$7.47)	32.35 ($\pm$7.73)	0.275
	Control	42.29 ($\pm$7.37)	46.99 ($\pm$9.70)	0.007[a]
Peak HR(beats per min)	*SCI*	165 ($\pm$24)	170 ($\pm$20)	0.342
	Control	180 ($\pm$9)	183 ($\pm$10)	0.059
RER(ratio)	*SCI*	1.25 ($\pm$0.07)	1.18 ($\pm$1.11)	0.016[a]
	Control	1.22 ($\pm$0.07)	1.19 ($\pm$0.7)	0.16

Abbreviations: HR, heart rate; RER, respiratory exchange ratio; SCI, spinal cord injury; VO_2, oxygen uptake.
[a]Significant difference ($P < 0.05$).

Sub-maximal exercise tests

During the sub-maximal treadmill walking exercise test, subjects in the SCI group exhibited significantly higher VO_2, HR and RER values at 30 W, and significantly higher HR and RER at 60 W, compared with those in the control group (Table 3). No statistically significant differences in cardiovascular responses during cycling were found between the groups, except for a higher RER value for the SCI group at 60 W (Table 3).

Mechanical efficiency

In the SCI group, three subjects were unable to perform the sub-maximal workload at 60 W on the treadmill. As the formula for mechanical efficiency requires a RER value <1, seven trails from the SCI group, were excluded from data analyses.

The net mechanical efficiency increased with workload during both stationary cycling and treadmill walking in both groups, (Table 4). Comparing within-subject net efficiency during stationary cycling and equivalent walking workloads revealed lower values during walking for both groups (Table 4).

The mean difference in net efficiency between cycling and walking were slightly higher at 30 W for the SCI group compared with the control group (Figure 1). The differences were, however, not statistically significant at either 30 W (-2.02 ± 1.7 %, $P = 0.24$) or 60 W (0.10 ± 2.4 %, $P = 0.97$).

DISCUSSION

Subjects with incomplete SCI exhibited comparable peak VO_2 and HR at maximal workloads during stationary cycling and treadmill uphill walking, whereas healthy controls achieved higher peak VO_2 during treadmill walking. In both groups, the mechanical efficiency at sub-maximal workloads was lower for the treadmill exercise than the cycle exercise.

The SCI subjects in the present study were classified as AIS D, and they had to be able to walk without assistive aids. As this subgroup represents a relative small part of the general SCI population, it should thus be noticed that the findings have implications only on this very specific population of the SCI individuals.

The lack of statistically significant difference in peak VO_2 between the treadmill and cycle exercise tests for the SCI subjects, as was found

Table 3 Cardiovascular responses (mean ± s.d. and *P*-values) in stationary cycling and treadmill walking at 30 and 60 watt for both SCI group and control group. Speed and incline (mean ± s.d.) is given for treadmill walking at both workloads

	30 watt			*60 watt*		
	SCI	*Control*	P*-value*	*SCI*	*Control*	P*-value*
Walking						
n	15	15		12	15	
Speed ($km\,h^{-1}$)[a]	3.1 (±0.5)	2.9 (±0.4)	0.34	4.1 (±0.5)	4.8 (±1.0)	0.04[b]
Incline (%)[a]	4.7 (±0.7)	4.9 (±0.5)	0.56	6,5 (±0.9)	6.2 (±1.0)	0.43
VO_2 ($l\,min^{-1}$)	1.18 (±0.23)	0.96 (±0.12)	<0.01[bc]	1.72 (±0.25)	1.48 (±0.25)	0.22[c]
VO_2 ($ml\,kg\,min^{-1}$)	14.83 (±1.9 4)	12.47 (±1.64)	<0.01[b]	20.24 (±2.42)	19.31 (±4.12)	0.51
HR (beats per min)	107 (±18)	85 (±6)	<0.01[b]	123 (±17)	104 (±12)	<0.01[bc]
RER (ratio)	0.90 (±0.06)	0.84 (±0.06)	0.03[b]	0.96 (±0.06)	0.89 (±0.05)	<0.01[b]
[La^-] ($mmol\,l^{-1}$)	1.16 (±0.42)	0.98 (±0.37)	0.33[c]	1.24 (±0.75)	0.91 (±0.39)	0.16
Cycling						
n	15	13		15	13	
VO_2 ($l\,min^{-1}$)	0.72 (±0.12)	0.72 (±0.10)	0.83[c]	0.99 (±0.13)	0.96 (±0.10)	0.45
VO_2 ($ml\,kg\,min^{-1}$)	9.13 (±1.43)	9.28 (±1.34)	0.78	12.74 (±2.31)	12.33 (±1.70)	0.60
HR (beats per min)	87 (±14)	81 (8)	0.16	99 (±15)	91 (±9)	0.13[c]
RER (ratio)	0.90 (±0.05)	0.86 (±0.04)	0.06	0.93 (±0.06)	0.87 (±0.04)	<0.01[bc]
[La^-] ($mmol\,l^{-1}$)	1.24 (±0.54)	0.88 (±0.40)	0.06[c]	1.09 (±0.34)	1.10 (±0.52)	0.95

Abbreviations: HR, heart rate; [La^-], blood lactate; SCI, spinal cord injury; RER, respiratory exchange ratio; VO_2, oxygen uptake.
[a]Speed and incline have been individually adjusted in the SCI group.
[b]Significant difference ($P<0.05$).
[c]*P*-values are calculated based on log transformed data due to non-normality.

Table 4 Comparison of the mean mechanical efficiency (± s.d.) during cycling and walking at 30 and 60 watt for both groups (SCI and control). Difference (± s.d.) and *P*-value between the exercise modes is given

	Cycling 30 watt	*Walking 30 watt*	*Difference*	*Cycling 60 Watt*	*Walking 60 Watt*	*Difference*
SCI	20.3 (±4.1) ($n=15$)	10.5 (± 2.3) ($n=14$)	9.8 (±4.0) $P<0.001$[a]	25.0 (±5.2) ($n=12$)	13.2 (± 2.1) ($n=8$)	11.8 (±5.2) $P<0.001$[a]
Control	21.4 (±4.7) ($n=13$)	13.6 (±1.8) ($n=15$)	7.7 (± 4.5) $P=0.001$[a]	26.6 (±3.9) ($n=13$)	15.0 (± 3.0) ($n=15$)	11.6 (±4.8) $P<0.001$[a]

Abbreviation: SCI, spinal cord injury.
[a]Significant difference ($P<0.05$).

for the healthy controls, might be explained by the physical limitations of the SCI subjects. Reduced balance, coordination, and muscle strength might limit peak VO_2 while walking at relatively high intensity. However, in spite of their reduced walking ability, subjects with SCI showed a slightly higher peak VO_2 and a somewhat lower perceived exertion during uphill walking versus cycling. The small sample size of the SCI group ($n=15$) is a limitation in this study. It is reasonable to assume that a larger sample size would have revealed a significant difference in peak VO_2 between the two exercise modes in the SCI group.

The protocol we used during the maximal exercise test on the treadmill consisted primarily of incline increases while walking at a comfortable speed. This protocol seems to be suitable for this patient group, because people with incomplete SCI adapt to a limited range of speeds.[17] To our knowledge, no other studies comparing SCI patient's peak VO_2 during cycling versus uphill walking have been published. Both the SCI and control groups demonstrated higher maximal workloads for the treadmill test compared with the stationary cycle test. Comparing maximal workload during treadmill exercise with other exercise modes like cycling is challenging. In contrast to cycle exercise, there is no linear relationship between workload and oxygen uptake during treadmill exercise at higher speeds.[18]

Several studies[19,20] have found that gait training improves walking ability in subjects with incomplete SCI. Uphill walking at high intensity might likewise have a positive effect on the walking ability in this population. Research has found that intensive walking training can increase energy expenditure and facilitate improvements in neuromuscular and cardiovascular function related to walking performance in SCI.[21]

When assessing results of maximal exercise testing, it is common to verify if subjects achieved maximal effort. Several criteria exist to evaluate the achievements of maximal exercise testing.[22] These criteria can include an occurrence of a VO_2 plateau, predicted (that is, age-related) maximal HR, RER values, blood lactate levels, and the Borg scale. However, comparing these criteria in two different exercise modes is challenging, especially when comparing a weight-bearing and a nonweight-bearing exercise mode. For example, during a maximal cycle exercise one expects higher values for blood lactate and RER and lower values for peak HR, as compared with a maximal running exercise.[23] In this study, 14 out of 15 subjects with incomplete SCI achieved criteria for both the $RER>1.10$ and Borg scale $\geqslant 17$ during

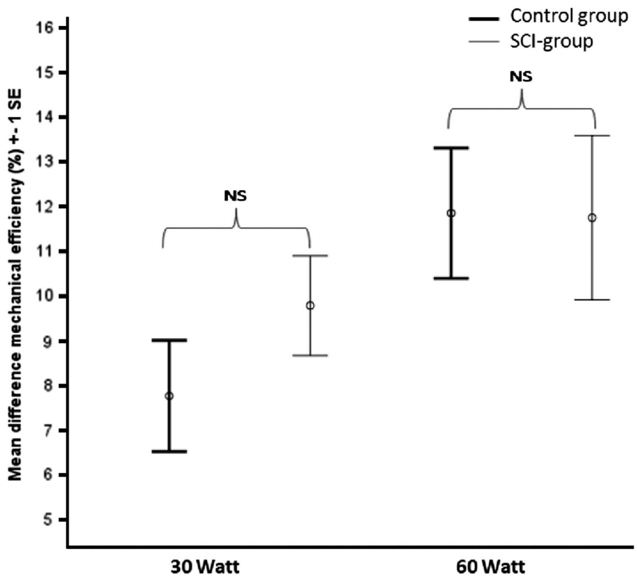

Figure 1 Between-groups differences in net efficiency (mean± 1 s.e.) between treadmill (uphill) walking and stationary cycling at two sub-maximal workloads (30 and 60 watt). SCI group, spinal cord injury group; NS, not significant.

maximal exercise testing on the stationary cycle. Twelve out of 15 subjects with incomplete SCI achieved both criteria during treadmill exercise, which suggests that most people with incomplete SCI are capable of performing high-intensity exercise at both exercise modes. Nevertheless, owing to strong heterogeneity in subjects with incomplete SCI, the optimal exercise mode for aerobic exercise should be determined individually. Further research should focus on the long-term training effects and optimal dose–response of aerobic training in this population.

Blood pressure and heart rate should be carefully monitored during exercise testing in persons with SCI, in order to be able to observe possible events of autonomic dysreflexia. All SCI subjects in this study have been examined by their medical doctor and none of these subjects had shown any signs of autonomic dysreflexia post-injury. Therefore, standard indications for terminating maximal exercise testing for healthy persons were used in this study.

Mechanical efficiency during cycling and walking at sub-maximal workloads did not differ between the SCI and control groups. This might indicate that persons with incomplete SCI with preserved walking ability do not use significantly more energy during walking and cycling at certain sub-maximal workloads compared to healthy persons. Our results contrast with other studies. Saraf *et al.*,[21] found that patients with SCI have a higher energetic cost of walking, compared with individuals who are neurologically intact. Scivoletto *et al*.[24] reported that balance, spasticity, and muscle strength negatively influenced walking performance in people with incomplete SCI. The dissimilar findings might be explained by differences in clinical characteristics of the subjects in these studies. In contrast to these two studies, our study only included SCI subjects who could walk for at least $4\,km\,h^{-1}$ in 5 min without assistive walking aids.

The formula used to calculate net efficiency (see equation (2)), requires a RER $<$ 1.0 when estimating E and REE. RER increases with exercise intensity, and when measured under steady state conditions it is commonly used to indirectly determine the relative contribution of carbohydrate and lipids to overall energy expenditure.[25] Owing to the low physical capacity of people with incomplete SCI, the intensity of the sub-maximal workloads was probably too high to reach a physiological steady state for some study subjects. Therefore, several trails in this study, especially in the SCI group, could not be used for data analyses, and thus reduced the statistical power.

On the other hand, the healthy subjects showed rather low mechanical efficiency during sub-maximal workloads, especially during the walking exercises. Efficiency normally ranges between 20 and 25% for walking,[11] whereas healthy study subjects showed average mechanical efficiencies of 13.6% and 14.5% during 30 and 60 W treadmill walking, respectively. This suggests that the speed at which the healthy subjects walked was most likely lower than their preferred walking speed, which might have negatively impacted their mechanical efficiency. Future studies might consider performing testing on a track, thereby allowing subjects to select their preferred walking speed.

CONCLUSIONS

People with incomplete SCI are capable of performing high-intensity weight-bearing exercise such as uphill treadmill walking. Compared with healthy controls, they showed similar mechanical efficiencies at sub-maximal workloads, but also a lower physical capacity (that is, peak VO_2). Weight-bearing, high-intensity aerobic training like uphill walking might be an effective training mode to achieve higher levels of physical capacity in people with incomplete SCI. More research is needed to investigate the long-term effects of both moderate and high-intensity aerobic training in this population.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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