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ORIGINAL RESEARCH

Cardiorespiratory Fitness in Individuals With Spinal Cord Injury: The Relationship With Motor Completeness

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Abstract

Objective: To compare cardiorespiratory fitness (CRF) in individuals with motor-complete spinal cord injury (SCI) with those with motor-incomplete SCI, while accounting for lesion level ("high" vs "low"). We hypothesized that individuals with motor-incomplete injuries would demonstrate higher CRF levels than those with motor-complete injuries, regardless of lesion level.

Design: Retrospective multicenter cohort study.

Setting: Dutch rehabilitation centers (N=12) involved in training participants for the HandbikeBattle event.

Participants: A total of N=217 individuals with SCI and a history of rehabilitation who participated in the HandbikeBattle event between 2013 and 2023 (excluding 2020-2022 due to the coronavirus disease 2019 pandemic) were included. The final analysis included 202 participants.

Interventions: Not applicable.

Main Outcome Measures: Indicators of CRF were peak oxygen uptake (Vo_2peak) and peak power output (PPO), assessed during a cardiopulmonary exercise test on an arm ergometer.

Results: Multilevel regression analyses showed that motor completeness of the lesion was not associated with either the relative or absolute values of Vo_2peak and PPO. Lesion level was associated with both Vo_2peak and PPO (relative and absolute), indicating that individuals with lower lesion levels had higher CRF outcomes than those with higher lesion levels.

Conclusions: CRF is not determined by the motor completeness of the lesion, but rather by the neurological level of injury. These findings indicate that CRF should be addressed in individuals with both motor-complete and motor-incomplete SCI. Exercise intensity and progression should be tailored to the individual's neurological level and functional capacity to optimize training adaptations. This knowledge may improve the clinical interpretation of fitness assessments and support more personalized exercise interventions for the SCI population.

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[1] HandbikeBattle group end of the document.

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Cardiorespiratory fitness (CRF) refers to the capacity of the circulatory and respiratory systems to deliver oxygen to skeletal muscles during physical activity and is a well-established predictor of morbidity and mortality in the general population.[1] In individuals with spinal cord injury (SCI), lower CRF is a widely recognized secondary health condition that impairs both health outcomes and quality of life.[2-4] This highlights the importance of understanding SCI-related factors associated with reduced CRF.

Previous research suggests that lesion characteristics, such as the neurological level of injury and motor completeness, may impact CRF. Individuals with higher lesion levels, defined as at or above the neurological level T6 (≥T6), generally exhibit lower CRF levels.[5] This may be related to more severe impairments in autonomic and motor functions, affecting blood flow to active musculature, muscle function, and trunk control.[5-7]

Similarly, motor completeness has also been considered a potential determinant of CRF. However, the existing literature remains inconsistent: some studies suggest an association with motor completeness, while others do not.[8-11] This inconsistency may reflect variations in population characteristics (eg, untrained vs athletic groups) and differences in how injury completeness is defined.[8-11]

Clarifying the role of motor completeness is clinically relevant, as current SCI exercise prescription guidelines largely provide generic recommendations that do not differentiate by injury completeness.[12] In addition, injury completeness may influence training adaptations.[6] Greater insight into the relationship between lesion completeness and CRF could therefore improve the clinical interpretation of fitness assessments and the tailoring of exercise interventions. The need for such clarity is amplified by the current demographic shift, with an increasing number of older individuals presenting with higher neurological levels and motor-incomplete lesions.[13] Ultimately, this knowledge could help refine clinical guidelines and reduce long-term health risks in this vulnerable population.

Therefore, the aim of this study was to compare CRF between individuals with motor-incomplete SCI and those with motor-complete SCI, while adjusting for lesion level ("high" vs "low"). We hypothesized that, independent of lesion level, individuals with motor-incomplete SCI exhibit a higher CRF than those with motor-complete SCI.

List of abbreviations:

AIS	**American Spinal Injury Association Impairment Scale**
BMI	**body mass index**
CH	**complete high**
CL	**complete low**
CPET	**cardiopulmonary exercise test**
CRF	**cardiorespiratory fitness**
DBP	**diastolic blood pressure**
HBB	**HandbikeBattle**
ICH	**incomplete high**
ICL	**incomplete low**
MAP	**mean arterial pressure**
PPO	**peak power output**
RERpeak	**peak respiratory exchange ratio**
RPE	**rating of perceived exertion**
SBP	**systolic blood pressure**
SCI	**spinal cord injury**
Vo_2peak	**peak oxygen uptake**

Methods

Study design

In this retrospective analysis, we used data from the HandbikeBattle (HBB) project, an observational cohort study that monitored participants before and after the training period for the HBB event, as well as 1 year after the event.[14] The HBB event is an annual handcycling mountain time trial of 20.2 km on the Kaunertaler Gletscherstrasse in Austria, in which teams from 12 Dutch rehabilitation centers compete. The HBB study received approval from the Ethics Committee of the Center for Human Movement Sciences at the University Medical Center Groningen, University of Groningen, the Netherlands (https://onderzoekmetmensen.nl/nl/trial/23899), and from the Ethics Committee of the Faculty of Behavioral and Movement Sciences, Vrije Universiteit Amsterdam, the Netherlands. All participants voluntarily signed informed consent. In this study, we used data collected only at the start of the HBB training period.

Participants

Data from HBB cohorts for 2013-2019 and 2023 were included, as no data were collected between 2020 and 2022 due to the coronavirus disease 2019 pandemic. Each cohort comprised a unique group of participants. Eligibility for the HBB study required prior completion of a rehabilitation program at a participating rehabilitation center, a lower-extremity impairment (eg, SCI, amputation, spina bifida, cerebral palsy), and a commitment to participate in the HBB challenge. Exclusion criteria comprised medical contraindications identified during screening and insufficient Dutch language proficiency. In the present study, only first-time HBB participants with SCI aged >18 years were included. Participants were excluded if data on CRF outcomes were missing or invalid, or if information on key SCI characteristics, including motor completeness and lesion level, was unavailable.

Procedures

Participants underwent assessments at their respective rehabilitation centers, including the collection of participant characteristics and CRF testing. Participant characteristics were obtained through medical screening and included sex, age, time since SCI onset, lesion level, and motor completeness. Injury level and motor completeness were evaluated by a trained rehabilitation physician using the International Standards for Neurological Classification of SCI (ISNCSCI).[15] Motor completeness was defined as American Spinal Injury Association Impairment Scale (AIS) categories A and B, while motor incompleteness was defined as AIS categories C and D.

A rehabilitation or sports physician performed a physical examination, including measurements of body mass index (BMI), waist circumference, blood pressure, resting heart rate, and respiratory function. BMI classification was based on the following SCI-specific cutoffs: recommended: BMI<22 kg/m^2; overweight: 22≤BMI<25 kg/m^2; and obese: BMI≥25 kg/m^2.[16] Blood pressure was measured as systolic blood pressure (SBP), diastolic blood pressure (DBP), and mean arterial pressure (MAP), with MAP calculated as (SBP+2*DBP)/3. Respiratory function was assessed using forced vital capacity, forced expiratory volume in 1 second, and peak expiratory flow.

CRF was assessed using a cardiopulmonary exercise test (CPET) involving synchronous arm cranking until volitional exhaustion. Test termination criteria were volitional exhaustion or failure to maintain a constant cadence above the preset value. Depending on the rehabilitation center, participants were tested using either an arm ergometer (Lode Angio)[a], or a sport handcycle mounted on a Tacx roller (Tacx)[b] at some centers, and a Cyclus 2 ergometer (RBM elektronik-automation GmbH)[c] at others. Test protocols varied across centers and involved either a 1-minute step protocol or a continuous ramp protocol. No systematic differences in CRF outcomes were expected between these protocols.[17] Gas exchange was measured using validated, frequently used systems, including a Cosmed device (COSMED)[d], a Cortex system (CORTEX Biophysik GmbH)[e], and an Oxycon system (Erich Jaeger, Viasys Healthcare)[f].

To evaluate whether CPET reflected true maximal effort, we assessed several indicators, including peak respiratory exchange ratio (RERpeak), peak heart rate, and rating of perceived exertion (RPE).[18] RERpeak was defined as the highest 30-second average value of the test, with the criterion RERpeak$\geq$1.10. Peak heart rate was defined as the maximum heart rate observed during the test, with the criterion peak heart rate$\geq$95%*(200$-$age). RPE was measured using Borg's category ratio (0-10) scale, where 0 represents "no exertion", and 10 indicates "maximum exertion"; a criterion of RPE$\geq$7 was applied. Although these standardized criteria are commonly used to indicate maximal effort in exercise testing, their application to individuals with SCI is limited.[19] For this reason, no strict exclusions based on these cutoffs were applied to the primary analyses.

Outcomes

The outcome measures were peak oxygen uptake (Vo_2peak) and peak power output (PPO). Vo_2peak was defined as the highest 30-second average oxygen consumption achieved during CPET. PPO was defined as the highest power sustained for at least 30 seconds during the step protocol or as the maximum power achieved during the ramp protocol. Both Vo_2peak and PPO were expressed relative to body mass (mL/kg/min and W/kg, respectively) and in absolute terms (L/min and W, respectively).

Statistical analysis

Participants were divided into 4 groups based on the level of neurological lesion and motor completeness. Lesion level was categorized as "high" ($\geq$T6) or "low" (<T6), and motor completeness as "complete" or "incomplete". This categorization resulted in the following groups: complete high (CH), incomplete high (ICH), complete low (CL), and incomplete low (ICL). To identify potential differences in participant characteristics across these 4 groups, a one-way analysis of variance was conducted for continuous variables, and a chi-squared test was used for categorical variables. If the one-way analysis of variance indicated a significant effect, post hoc pairwise comparisons were performed to identify between-group differences.

To assess the impact of motor completeness on relative and absolute CRF outcomes (Vo_2peak and PPO), multilevel linear regression analyses were performed. Two-level multilevel models were constructed with participants at level 1 and rehabilitation centers at level 2, to account for dependence among participants nested within centers. Independent variables included injury completeness, lesion level, the interaction term between them, and age. Lesion level and age were included based on prior evidence demonstrating their influence on CRF performance in the SCI population.[8-11,20] The interaction term was included to assess whether the effect of completeness on CRF differed by lesion level.

Sensitivity analyses were performed to assess the robustness of the findings. Participants who did not meet at least 2 of the 3 predefined maximal effort criteria (as described above) were excluded. Multilevel regression analyses were repeated on the reduced sample and compared with the primary analyses.

Assumptions of normality, linearity, and multicollinearity were checked before analyses. Continuous variables were presented as mean±SD, whereas categorical variables were expressed as counts and percentages. A significance level of $P<.05$ was applied to all analyses. Data analysis was performed using R version 4.4.2[g] and MLwiN version 2.36.[h]

Results

Participant characteristics

The HBB study initially included 217 individuals with SCI between 2013 and 2023. Participants were excluded due to missing or invalid CRF outcomes (n=8) or missing data on SCI characteristics (n=4). An additional 3 participants were excluded for being <18 years of age, resulting in a total of 202 individuals included in the analyses.

Most participants in the CH and CL groups were classified as AIS category A (81% and 84%, respectively). In the ICH group, AIS category D was most prevalent (63%), whereas the ICL group showed a nearly equal distribution between AIS categories C and D. General characteristics did not differ among the 4 groups, except for BMI, which was higher in the ICL group than in the CH and CL groups (table 1). According to the SCI-specific BMI cutoff values, 80% of ICH participants and 86% of ICL participants were classified as overweight or obese, compared with 61% and 58% in the CH and CL groups, respectively. No differences were observed in resting hemodynamic measures, respiratory function tests, or indicators of maximal effort between participants with complete versus incomplete lesions, irrespective of lesion level (table 1). Blood pressure, forced vital capacity, and peak heart rate were lower in the CH group than in the CL group (table 1).

Impact of motor completeness on CRF outcomes

Age was inversely associated with relative Vo_2peak ($-$0.12 mL/kg/min per additional year of age), supporting the inclusion of age in the regression model. The regression analysis showed no association between relative Vo_2peak and motor completeness, nor between relative Vo_2peak and the interaction between injury completeness and lesion level (fig 1). Individuals with lower lesion levels had higher relative Vo_2peak values than those with higher lesion levels (fig 1 and table 2). No association was found between absolute Vo_2peak and motor completeness, whereas an association was observed with lesion level (supplemental fig S1, available online only at http://www.archives-pmr.org/). Detailed results of the multilevel regression analyses are reported in supplemental tables S1-S4 (available online only at http://www.archives-pmr.org/).

Age was inversely associated with relative PPO, with each additional year corresponding to an average decrease of

Table 1 Participant Characteristics of the Total Study Population, Distributed Over 4 Subgroups Based on Completeness and Lesion Level.

Characteristics	CH n=54	ICH n=30	CL n=69	ICL n=49	Total n=202	*P* Value	Motor Completeness Difference CH vs ICH; CL vs ICL	Lesion Level Difference CH vs CL; ICH vs ICL
General characteristics								
Sex, men	45 (83)	23 (77)	55 (80)	36 (73)	159 (79)	.66		
Age (y)	40±12	47±13	41±11	43±11	42±12	**<.05**	No difference	No difference
Time since injury (y)	8.6±10.1	7.7±9.3	9.1±10.2	7.6±8.8	8.4±9.7	.85		
	n=49	*n=28*	*n=65*	*n=46*	*n=188*			
BMI (kg/m^2)	23.7±3.8*	25.7±4.0†	23.4±3.7	25.8±4.2	24.4±4.0	**<.01**	CL<ICL	
	n=53	*n=29*	*n=67*	*n=48*	*n=197*			
Waist circumference (cm)	91.6±16.1	96.5±11.7	90.5±14.5	95.4±12.5	93.0±14.1	.19		
	n=42	*n=26*	*n=53*	*n=40*	*n=161*			
Hemodynamic measures at rest								
SBP (mmHg)	119±16*	127±17	136±19	131±16	129±18	**<.001**		CH<CL
	n=42	*n=26*	*n=58*	*n=41*	*n=167*			
DBP (mmHg)	74±10*	77±11	82±11	82±11	79±11	**<.001**		CH<CL
	n=42	*n=26*	*n=58*	*n=41*	*n=167*			
MAP (mmHg)	89±11*	94±11	100±13	98±12	96±13	**<.001**		CH<CL
	n=42	*n=26*	*N=58*	*n=41*	*n=167*			
Heart rate (beats/min)	71±14	70±12	73±12	71±10	72±12	.72		
	n=41	*n=26*	*n=56*	*n=38*	*n=161*			
Respiratory function tests								
Forced vital capacity (L)	3.9±0.8*	4.5±1.1	4.6±1.1	4.9±1.0	4.5±1.1	**<.001**		CH<CL
	n=43	*n=25*	*n=56*	*n=39*	*n=163*			
Forced expiratory volume in 1 s (L)	3.3±0.8*	3.6±0.9	3.6±0.8	3.9±0.8	3.6±0.8	**<.01**		
	n=43	*n=25*	*n=56*	*n=39*	*n=164*			
Peak expiratory flow (L/s)	7.3±1.8*	7.4±1.9	8.2±2.2	8.6±2.0	8.0±2.1	**<.01**		
	n=41	*n=25*	*n=56*	*n=39*	*n=161*			
Indicators of maximal effort								
RERpeak	1.23±0.15	1.16±0.12†	1.27±0.13	1.25±0.11	1.24±0.13	**<.01**		ICH<ICL
	n=51		*n=62*		*n=192*			
Peak heart rate (beats/min)	156±34*	153±28†	174±13	174±15	166±24.7	**<.001**		CH<CL, ICH<CL
		n=29	*n=67*		*n=199*			
RPE	7.4±1.5	8.3±1.5	7.5±1.6	8.0±1.5	7.8±1.6	**.05**		
	n=40	*n=26*	*n=42*	*n=33*	*n=141*			

Data are presented as n (%) or mean±SD for the total study population and for the 4 subgroups: CH, ICH, CL, and ICL. In cases of missing data, the corresponding sample size is reported. Bold values indicate statistically significant differences ($P<.05$). Post hoc pairwise comparisons shown in separate columns reflect differences based on motor completeness and lesion level are indicated as *$P<.05$ for CH vs ICL; †$P<.05$ for ICH vs CL. Among participants with complete data on maximal effort variables (n=138), 93% met at least 2 of 3 criteria for maximal effort during CPET.

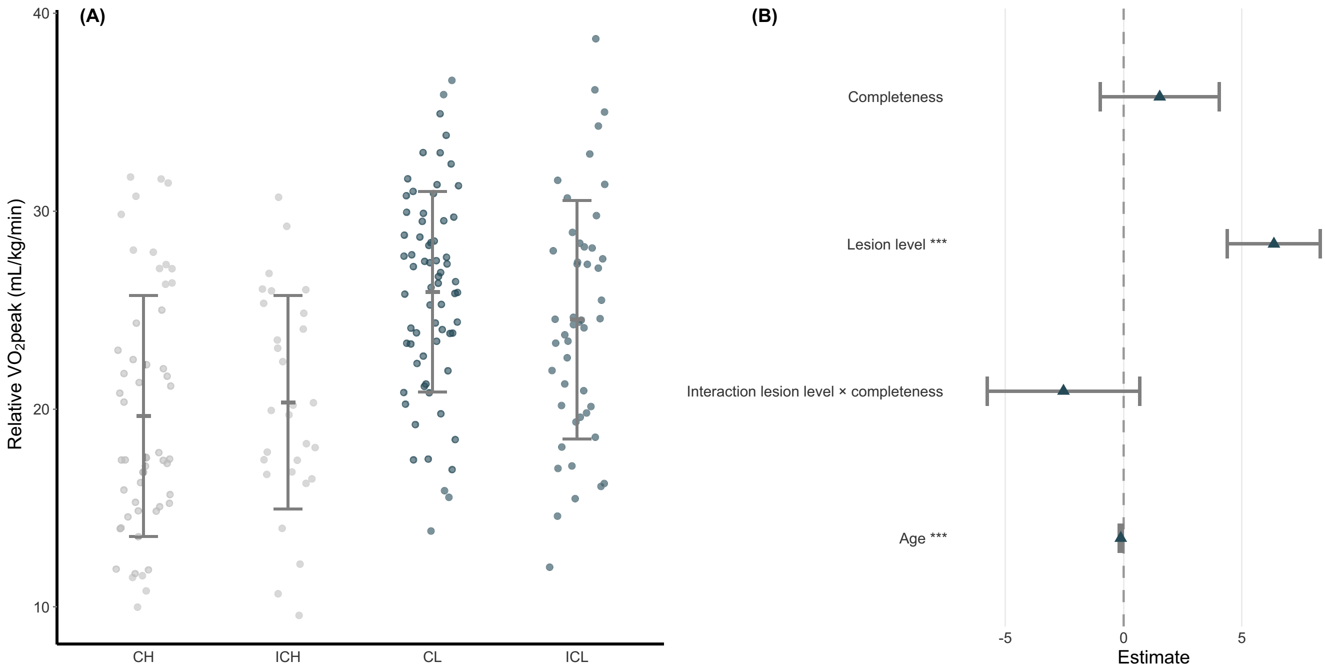

Fig 1 Descriptive statistics and regression analysis of relative Vo_2peak. (A) Individual data points and group means ±SD for relative Vo_2peak across the 4 groups: CH (n=54), ICH (n=30), CL (n=69), and ICL (n=49). (B) Results of the multilevel regression analysis, illustrating the associations between predictors and relative Vo_2peak. Error bars represent 95% confidence intervals. ***$P<.001$.

0.01 W/kg, thereby supporting its inclusion in the regression model. The regression analysis revealed that relative PPO was not associated with motor completeness, nor with the interaction between motor completeness and lesion level (fig 2). Lesion level was associated with relative PPO, with individuals with lower lesion levels demonstrating higher values than those with higher lesion levels (table 2 and fig 2). Absolute PPO was not associated with motor completeness, but was associated with lesion level (supplemental fig S2, available online only at http://www.archives-pmr.org/).

Sensitivity analyses

Sensitivity analyses excluding participants who did not meet predefined maximal effort criteria (n=10) were performed on the remaining 192 participants, and these analyses did not alter the results of the primary multilevel regression analyses (supplemental tables S5-S8, available online only at http://www.archives-pmr.org/).

Discussion

This study included direct CRF measurements using the reference CPET protocol in 202 individuals with SCI and examined whether motor completeness of the lesion was associated with CRF level. We found that motor completeness was not associated with relative or absolute Vo_2peak or PPO, an observation that was independent of lesion level. Furthermore, lesion level was highlighted as an important determinant of CRF outcomes, with individuals with higher lesion levels demonstrating lower CRF values than those with lower lesion levels. These findings suggest that the neurological level of injury, rather than motor completeness, is related to CRF in individuals with SCI.

Table 2 CRF of the Total Study Population and 4 Subgroups Based on Completeness and Lesion Level.

Cardiorespiratory fitness outcomes	CH n=54	ICH n=30	CL n=69	ICL n=49	Total n=202
Relative values					
Vo_2peak (mL/kg/min)	19.7±6.1	20.3±5.4 *n=29*	25.9±5.1 *n=68*	24.5±6.0 *n=48*	23.1±6.2 *n=199*
PPO (W/kg)	1.2±0.4	1.2±0.4 *n=29*	1.7±0.4 n=68	1.6±0.4 *n=48*	1.5±0.5 *n=199*
Absolute values					
Vo_2peak (L/min)	1.5±0.5	1.7±0.4	1.9±0.5	2.0±0.5	1.8±0.5
PPO (W)	93.8±30.6	95.4±34.6	126.5±34.5	129.6±29.9	113.9±36.2

Data are presented as mean±SD for the total study population and for the 4 subgroups: CH, ICH, CL, and ICL. In cases of missing data, the corresponding sample size is reported.

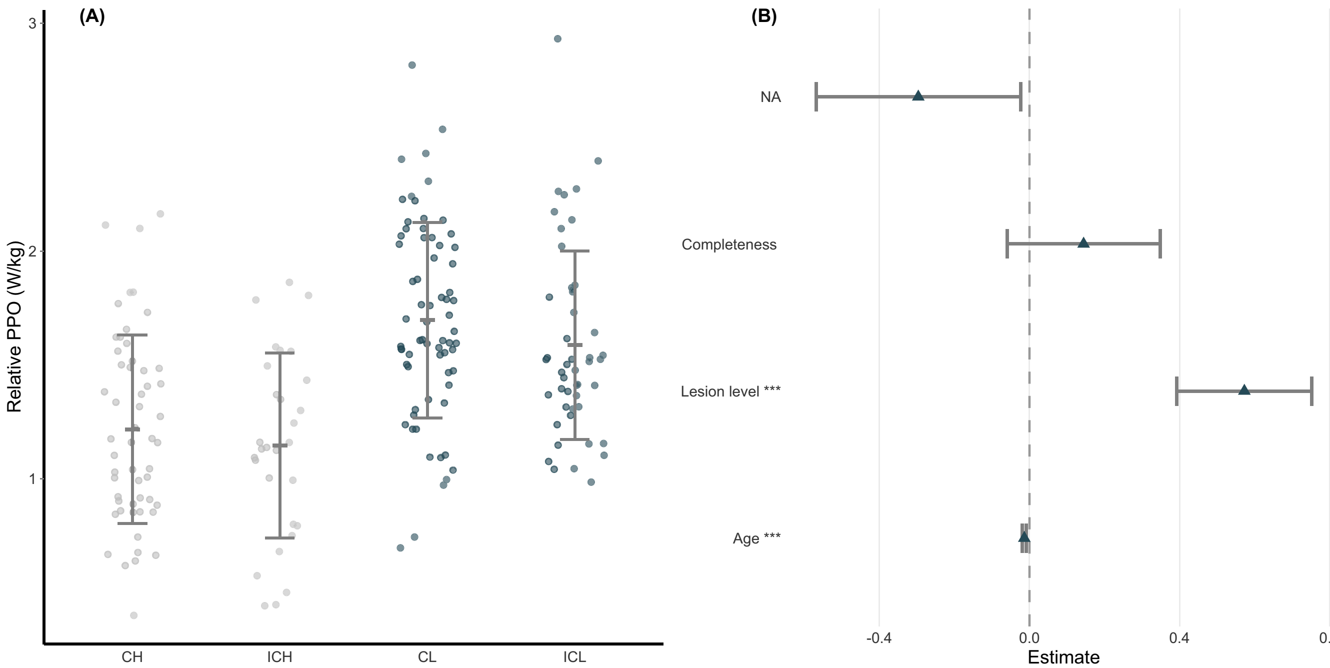

Fig 2 Descriptive statistics and regression analysis of relative PPO. (A) Individual data points and group means ±SD for relative PPO across the 4 groups: CH (n=54), ICH (n=30), CL (n=69), and ICL (n=49). (B) Results of the multiple regression analysis, illustrating the associations between predictors and relative PPO. Error bars represent the 95% confidence intervals. ****P*<.001.

The observation of comparable CRF outcomes between individuals with motor-complete and motor-incomplete SCI was contrary to our hypothesis. Given the greater neuromuscular impairment associated with motor-complete injuries, we anticipated lower CRF in this group than in those with motor-incomplete SCI, who retain partial voluntary motor function.[6,7] This result raises the possibility that other factors, such as autonomic impairment, may have a greater influence on CRF outcomes than motor completeness. The relevance of additional factors is supported by the relatively low R^2 values of our models (ranging from 0.15 to 0.33; see supplemental tables S1-S4), indicating that a substantial proportion (67%-85%) of the variance in relative and absolute CRF outcomes remains unexplained. This highlights the need for further research to identify and understand the factors contributing to CRF in individuals with SCI.

A factor potentially explaining CRF outcomes may relate to autonomic (dys)function, especially since autonomic impairment is primarily determined by lesion level rather than by motor completeness of the injury.[21] Indeed, lesion level was an important predictor of CRF outcome in the present study. Individuals with higher lesion levels may experience impaired sympathetic innervation, which can blunt cardiovascular responses to exercise.[22] Supporting this assumption, we found that participants with motor-complete SCI and a high lesion level demonstrated a significantly lower peak heart rate during CPET than those with lower lesion levels. This severely limits cardiac output, a key determinant of CRF.[7] Another factor supporting impaired sympathetic innervation in individuals with a high lesion level is the observation of lower blood pressure (SBP, DBP, MAP) in those with motor-complete SCI. Lower blood pressure levels were not observed in individuals with high motor-incomplete SCI. Reduced blood pressure in individuals with a high, motor-complete SCI may reflect impaired autonomic control, as blood pressure is primarily regulated by the autonomic nervous system.

Alternative factors contributing to CRF in individuals with SCI may include individual characteristics such as age. In the present study, age was negatively associated with both relative Vo_2peak and PPO, suggesting that older individuals with SCI may experience reduced cardiorespiratory capacity. This finding aligns with the results of Janssen et al,[8] who similarly reported an inverse relationship between age and CRF in individuals with SCI.[8] However, contrary to our findings, Janssen et al[8] also identified an association between motor completeness and CRF. Several methodological differences may account for this discrepancy. For example, their study included a younger population and used a different classification system for lesion level. Moreover, they accounted for activity level in their analysis, a variable not incorporated in the current study, which may also partly explain the divergent results.

To further contextualize our findings, we examined the absolute Vo_2peak values in our study population, which ranged from 1.5 to 2.0 L/min across the 4 subgroups (table 2). Although normative data for arm-cranking Vo_2peak are limited, existing studies suggest that Vo_2peak values obtained through arm ergometry are typically about 70% of those observed during leg cycling in able-bodied participants.[23] Based on this ratio, expected Vo_2peak values would range from approximately 2.1 to 2.9 L/min. Compared with our predominantly male cohort, these values are relatively lower than those observed in the general population.[24] This highlights the need for targeted interventions to improve CRF and reduce the associated risk for cardiovascular disease, especially in individuals with SCI and higher lesion levels who are more likely to experience more severe cardiovascular and respiratory impairments.

Study limitations

This study has some limitations. First, selecting individuals participating in a demanding handcycling mountain event likely introduced selection bias, as participants were generally more physically active than the general SCI population. Consequently, individuals with very low physical capacity or limited motivation for exercise may be underrepresented, limiting the generalizability of our findings to the broader SCI population. Second, participants younger than 18 years and those with missing or invalid data (<7%) were excluded. As these participants were limited in number and distributed across centers, missingness was considered random and unlikely to have biased the results. Third, the multicenter design introduced variability in testing procedures, as measurements were conducted across 12 rehabilitation centers. Differences in equipment, testing protocols, and environmental conditions may have influenced the consistency of the results. While standardized protocols were used to minimize these discrepancies, some variation was inevitable in a multicenter setting. Therefore, multilevel analyses were conducted to account for dependence among participants within centers. Finally, upper-body exercise testing may not have elicited a true maximal cardiorespiratory response in all individuals. In particular, for individuals with motor-incomplete, low-level SCI who retained voluntary activation of the lower-extremity musculature, a graded exercise test on a treadmill or cycle ergometer would have been the preferred modality. As these individuals might have achieved higher Vo_2peak values on a treadmill or cycle ergometer, true peak CRF may have been underestimated in this subgroup. This limitation should be considered when interpreting direct comparisons in the present study and in studies using different testing modalities. However, arm crank ergometry was deliberately chosen to ensure methodological consistency and feasibility across the full spectrum of SCI, including individuals with motor-complete lesions for whom lower-body exercise is not possible.

Conclusions

This study examined the impact of motor completeness on CRF while accounting for lesion level and age. The findings indicate that motor completeness is not associated with either Vo_2peak or PPO, whereas individuals with higher neurological lesion levels consistently demonstrated lower CRF outcomes than those with lower lesion levels. These results suggest that the neurological level of injury, but not motor completeness, is related to CRF. This underscores the importance of addressing and monitoring CRF in individuals with both motor-complete and motor-incomplete SCI. Moreover, the observed influence of the neurological level of injury highlights the need for personalized exercise prescriptions and progression monitoring based on the neurological level and functional capacity to optimize training adaptations and improve the clinical interpretation of fitness assessments in this population.

HandbikeBattle group

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Suppliers

a. Lode Angio, Groningen, the Netherlands
b. Tacx, Terneuzen, the Netherlands
c. RBM elektronik-automation GmbH, Leipzig, Germany
d. COSMED, Roma, Italy
e. CORTEX Biophysik GmbH, Leipzig, Germany
f. Erich Jaeger, Viasys Healthcare, Friedberg, Germany
g. R version 4.4.2; R Core team, 2025, Vienna, Austria
h. MLwiN version 2.36, University of Bristol, United Kingdom

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the authors used ChatGPT and Microsoft 365 Copilot in order to assist with spelling, grammar, and improving scientific writing style. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Keywords

Cardiorespiratory fitness; Exercise test; Rehabilitation; Spinal cord injuries

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