

1 Maximal and Submaximal Aerobic Tests for Wheelchair-Dependent Persons with Spinal  
2 Cord Injury: A Systematic Review to Summarize and Identify Useful Applications for  
3 Clinical Rehabilitation.

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5 Sophia Eerden, Msc,<sup>a</sup> Rienk Dekker, PhD,<sup>b,c</sup> Florentina J. Hettinga, PhD<sup>d</sup>

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7 a. University of Groningen, University Medical Center Groningen, Center for Human  
8 Movement Sciences, Groningen, The Netherlands

9 b. Department of Rehabilitation Medicine, Center for Rehabilitation, University Medical  
10 Center Groningen, Groningen, The Netherlands

11 c. Center for Sports Medicine, University Medical Center Groningen, Groningen, The  
12 Netherlands

13 d. University of Essex, School of Biological Sciences, Centre of Sport and Exercise Science,  
14 Colchester, United Kingdom

15

16 Corresponding author:

17 Florentina J. Hettinga

18 Address: Wivenhoe Park CO3 4SQ Colchester

19 Telephone: +441206872046

20 E-mail: fjhett@essex.ac.uk

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25 Maximal and Submaximal Aerobic Tests for Wheelchair-Dependent Persons with Spinal  
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27 Clinical Rehabilitation.

28

29 **Purpose:** To summarize the available maximal and submaximal aerobic exercise tests for  
30 wheelchair-dependent persons with a spinal cord injury and to identify useful applications for  
31 clinical rehabilitation.

32 **Method:** The databases of PubMed, CINAHL<sup>®</sup>, EMBASE and PsycINFO<sup>®</sup> were searched for  
33 English-language studies published prior to March 2015. Two independent raters identified  
34 and examined studies that reported on laboratory-based aerobic exercise tests in persons with  
35 a spinal cord injury, according to the PRISMA statement.

36 **Results:** The test protocols of maximal (n = 105) and submaximal (n = 28) exercise tests,  
37 covered by 95 included studies, were assessed. A large variety in patient characteristics, test  
38 objectives, test protocols, exercise modes and outcome parameters was reported. Few studies  
39 reported on adherence to recommendations, adverse events and peak outcome validation.

40 **Conclusion:** An incremental test protocol with small, individualized, increments per stage  
41 seems preferable for testing maximal aerobic capacity, but additional validation of the  
42 available test modes is required to draw conclusions. Submaximal testing is relevant for  
43 assessing the performance at daily life intensities and for estimating  $VO_{2peak}$ . Consensus  
44 regarding reporting test procedures and outcomes needs to be achieved to enhance  
45 comparability of rehabilitation results.

46

47 **Keywords:** cardiopulmonary exercise test; rehabilitation outcome; wheelchair; upper  
48 extremity; spinal cord injuries.

49

## 50 INTRODUCTION

51 Individuals with a spinal cord injury (SCI) have difficulties to engage in physical activities  
52 since they experience poor accessibility and fewer opportunities to be physically active. As a  
53 result, these persons often show lower physical activity levels when compared with  
54 ambulatory individuals and, consequently, are at risk for the development of medical  
55 complications (1-3). Increasing the aerobic capacity of persons with a SCI during  
56 rehabilitation is essential for the prevention of low physical fitness levels (4). In order to  
57 monitor and optimize effects of rehabilitation training it is recommended to quantify changes  
58 in the aerobic capacity of patient with SCI during rehabilitation (5). To do so, it is important  
59 that the characteristics of the available aerobic exercise tests for individuals with a SCI are  
60 explored and judged on their applicability in the rehabilitation practice. The current review  
61 will therefore summarize the available maximal and submaximal exercise tests for  
62 wheelchair-dependent persons with a SCI.

63 Over the past few decades, a variety of different upper-body exercise testing modes  
64 and protocols has been conducted in the SCI population. As indicated in the study of Valent et  
65 al. (2007), differences in exercise test designs to measure physical capacity might influence  
66 the test results. The validity of the reported improvements in peak oxygen uptake ( $VO_{2peak}$ )  
67 and peak power output ( $PO_{peak}$ ) after training is therefore questionable (6). The  $VO_{2peak}$  and  
68  $PO_{peak}$  parameters are, according to the American College of Sports Medicine (ACSM),  
69 considered to be the gold standard for indicating a persons' peak physical capacity (7, 8). The  
70 disparity in testing protocols and outcomes hampers the process of interpreting findings,  
71 makes it difficult to compare trends across studies, and impedes generalization of the results  
72 to the larger SCI population (9). At the same time, the implementation of evidence-based  
73 practice in SCI health care has become increasingly important over the past ten years.  
74 Furthermore, as pointed out by De Groot et al. (2010), there is a strong basis for

75 implementing standardized tests in SCI rehabilitation centers, which emphasizes the practical  
76 possibilities of the development of a standardized aerobic exercise test (5). These findings  
77 emphasize the necessity of a thorough evaluation of the available aerobic exercise test for  
78 people with a SCI, as a first step towards the development of standardized testing.

79         Regular testing a patient with SCI throughout the rehabilitation process with a  
80 standardized aerobic exercise test can provide very valuable information. It enables  
81 rehabilitation professionals to monitor and evaluate the patients' progress and to make  
82 specific adjustments in the training program. This adequate training will support patients in  
83 the performance of daily life activities, which is an important goal for rehabilitation, and it  
84 would contribute to improve rehabilitation outcomes (4, 5). In order to develop evidence-  
85 based exercise and fitness monitoring in rehabilitation practice, a first step is to explore the  
86 available aerobic testing protocols that have been applied in the SCI population. Therefore,  
87 the aims of this systematic review are to summarize the available maximal and submaximal  
88 aerobic exercise tests for wheelchair-dependent persons with a SCI (i) and to identify useful  
89 applications for clinical rehabilitation (ii).

90

## 91 **METHODS**

92

### 93 **Search strategy**

94 This systematic review was conducted in accordance with the recommendations of PRISMA  
95 (Preferred Reporting Items for Systematic Reviews and Meta-analysis) (10). The electronic  
96 databases of PubMed, CINAHL<sup>®</sup>, EMBASE and PsycINFO<sup>®</sup> were systematically searched on  
97 studies published prior to May 2013. An updated search was performed in March 2015 and  
98 May 2016, by using the same search strategy. A comprehensive search strategy was built,

99 consisting of a combination of database-specific MeSH terms, free text, 'wild cards' (words  
100 truncated by using "\*\*") and Boolean operators ("AND", "OR", "NOT"). The search was  
101 structured into three parts, with the first part concerning population keywords (spinal cord  
102 injury, paraplegia, tetraplegia, wheelchair). The second part of the search strategy refers to  
103 studies about wheelchair propulsion-related aerobic exercise tests. The used keywords were  
104 exercise test, maximal, submaximal, physiologic fitness and training. For the third part of the  
105 search, that covered the possible outcome measures of exercise tests, keywords were i.e.  
106 oxygen consumption, power output and heart rate. All three parts of the search were  
107 combined using the Boolean operator "AND". Retrieved papers (n = 1211) were combined in  
108 a single database and duplicates (n = 191) were removed.

109

## 110 **Study selection**

111 In order to be included in the current review, studies had to meet the following criteria: (1)  
112 >80% of the experimental study group has a SCI, (2) a laboratory-based aerobic exercise test  
113 is included, (3) and a description of the initial settings and stages of the testing protocol is  
114 provided. Exclusion of studies occurred if they only reflected on anaerobic testing, body  
115 weight support training, respiratory training, functional electrical stimulation, quality of life  
116 assessment, body temperature examination, activities of daily living, electromyography,  
117 electrocardiography, homeostatic processes or metabolic responses, since these outcomes  
118 were not directly related to physical capacity. Additionally, any other type of article than an  
119 experimental or observational research article was excluded, including a review of the  
120 literature or a comment to the editor.

121

## 122 **Screening**

123 The flow diagram of literature searches and results is shown in figure 1. After removing  
124 duplicates, 1020 articles were identified. In the first and second screening stage, two authors  
125 (RD and SE) independently screened the titles and abstracts respectively, according to  
126 inclusion and exclusion criteria. In case of persisting disagreement during any of these two  
127 assessment phases, a third observer (FJH) gave a binding verdict. Agreement between the  
128 authors during the title- and abstract assessment phase, expressed with Cohens Kappa, was  $\kappa$   
129 = 0.572 and  $\kappa = 0.487$  ( $p < 0.001$ ) respectively. Full agreement (100%) was achieved during  
130 a consensus meeting that was held for each phase. Ninety-six articles were retained for full  
131 text assessment, but nine of these 96 articles were unavailable despite several attempts of the  
132 authors to retrieve them. In the second screening stage, 87 articles were read by RD and SE  
133 and were included when both reviewers felt they met all the inclusion criteria. Subsequently,  
134 24 were excluded based on these inclusion criteria. Respectively three and four more articles  
135 were included after the updated searched in March 2015 and May 2016. Additionally, 25  
136 eligible articles were found after checking the reference lists. A total of 95 articles were rated  
137 as eligible to be included for review.

138

139 Insert figure 1.

140

#### 141 **Data extraction**

142 The three authors together established a data extraction form. Author SE completed these data  
143 extraction forms for the included 95 studies accordingly. Relevant study characteristics were  
144 extracted and described: (i) population characteristics, (ii) the test protocol used to conduct  
145 the aerobic exercise test and termination guidelines referred to, (iii) the criteria used to  
146 determine maximal performance, (iv) adverse events during testing and (v) key measurement

147 outcomes reported, namely oxygen uptake, power output, respiratory exchange ratio and heart  
148 rate.

149

## 150 **RESULTS**

151

152 A total of 89 incremental maximal exercise tests, 14 intermittent maximal exercise tests, 2  
153 constant load maximal exercise tests and 28 submaximal exercise tests were conducted among  
154 the 95 included studies. The extracted study and population characteristics are shown in Table  
155 1. Table 2 and 3 present the protocol details and outcomes for the maximal aerobic tests and  
156 submaximal aerobic tests, respectively.

157

158 Insert table 1.

159

### 160 **Patient characteristics**

161 Based on 95 articles, a total of 2,725 participants were included in the analysis. The number  
162 of participants included in a study ranged from 1 (33) to 185 (4). Mean age ranged from 24  
163 (33, 66) to 50.0 (50) years. Most studies included more men than women, but 46 studies  
164 included only men. Mean time since injury (TSI) ranged from 78 days (52) to 28.7 years (25)  
165 and lesion level ranged from C1 (82) to S2 (43, 45). Forty-four studies included only persons  
166 with a paraplegia, whereas 10 studies only included persons with a tetraplegia. Forty studies  
167 described both persons with a tetraplegia and paraplegia. One study did not report on the  
168 lesion level of the included participants. Completeness of the injury was assessed in 67 of the  
169 95 studies. A total of 46 of these 95 studies included both subjects with a complete and  
170 incomplete lesion, whereas 21 studies included solely persons with a complete lesion. The

171 reported fitness of the participants ranged from persons with a low physical fitness status  
172 (rehabilitants, sedentary, untrained and inactive people) to persons with a high physical fitness  
173 status (athletes, active, trained people).

174

### 175 **Study designs**

176 In the majority of the included studies, a single measure design was applied (n = 44). Twenty-  
177 two studies were registered as a pre-post training design, whereas 17 studies conducted  
178 repeated measures. Nine studies applied a prospective cohort design, of which eight studies  
179 were the result of the cohort study titled 'Physical strain, work capacity, and mechanisms of  
180 restoration of mobility in the rehabilitation of persons with spinal cord injuries'. Other study  
181 designs were registered as well, including a randomized controlled trial (n = 2) and a case  
182 study (n = 1). Sixteen of the included studies included a control group in the study design,  
183 which consisted of either persons with a SCI (n = 3) or able-bodied persons (n = 13). The  
184 remaining 79 studies did not include a control group.

185

### 186 **Test objectives**

187 The main test objectives identified for the aerobic exercise tests were to determine  
188 physiological responses (max: n = 48, submax: n = 8), to assess the effect of training or  
189 rehabilitation on physical capacity (max: n = 26, submax: 5) or to describe the relationship  
190 between two parameters (max: n = 13, submax: 4). Other identified objectives were to screen  
191 for contraindications for training (max: n = 1), to determine  $VO_{2peak}$  for additional training or  
192 testing protocols (max: n = 2), to examine the reliability of the six-minute push test (max: n =  
193 1) and a graded submaximal test (submax: n = 1), to determine measurement properties of  
194 fitness measures (n = 1), to determine increments per stage for a subsequent maximal test  
195 (submax: n = 1) or to determine the a steady state submaximal performance submax: n = 1).



196 The test objective of seven submaximal tests was not reported.

197

### 198 **Exercise modes**

199 In 52 of the 105 performed maximal exercise tests, an arm crank ergometer was used to  
200 conduct the exercise test. The wheelchair ergometer was used in 44 tests and the hand cycle in  
201 6 tests. Other identified exercise modes were supine arm crank ergometry (n = 1), arm  
202 tracking, which is a dual action exercise ergometer, (n = 1) and seated double poling  
203 ergometry (n = 1). For conducting the 28 submaximal exercise tests, wheelchair ergometry (n  
204 = 13) and arm crank ergometry (n = 10) were used, as well as the hand cycle (n = 3), supine  
205 arm crank ergometry (n = 1) and seated double poling ergometry (n = 1).

206 When relating the identified aerobic fitness indications to the used exercise modes, it  
207 appears that active or trained participants were involved in 35% of the studies that used  
208 wheelchair ergometry, rehabilitants in 30% of these studies, athletes in 21% and inactive or  
209 untrained participants in 5% of these studies. The aerobic fitness indication was not reported  
210 in 9% of the studies. For the arm crank ergometry, somewhat similar results were found, but  
211 fewer rehabilitants were involved in these studies (14%) and a higher number of studies did  
212 not reported on aerobic fitness indication (29%). For hand cycling studies, active participants  
213 (67%) and rehabilitants (33%) performed the exercise tests.

214

215 Insert table 2.

216

### 217 **Test protocols**

218 A warm-up was performed prior to the actual test protocol in 42 maximal exercise tests and  
219 six submaximal exercise tests. The warm-ups had a duration of one to five minutes and were

220 performed at zero or low resistance loads. The reported propulsion speed ranged from 3 to 8.5  
221 km/h or 50-60 rpm.

222 For most maximal exercise test protocols, the time to exhaustion varied between six to  
223 15 minutes. The shortest time to exhaustion was found in the study of Lasko-McCarthy &  
224 Davis (1991), in which the tests was ended after 4.51 minutes (69). The study of McLean et  
225 al. (1995) reported the longest time to exhaustion of over 20 minutes (78). This study  
226 involved an intermittent maximal test protocol in which exercise periods were alternated with  
227 80 seconds rest periods.

228 Three different maximal test protocols was used, namely incremental, intermittent and  
229 constant load maximal exercise tests. These protocols will now be further described, as well  
230 as the test protocols of submaximal exercise tests.

231 *Incremental maximal exercise tests.* Four different test protocols were described for the 89  
232 incremental tests. Most of these tests (n = 68) increased activity by increasing loads or  
233 resistance. The size of these increments ranged from 3 to 15W per 1 to 3 minutes for tests  
234 conducted with a wheelchair ergometer. For the tests using arm crank ergometry and hand  
235 cycling, step sizes ranged from 2W to 30W with step duration ranging from 1 to 3 minutes.  
236 Several studies used different incremental steps, depending on the participants' lesion level  
237 (20, 50, 57, 67-69, 74, 81, 82, 84, 94, 98). Participants were instructed to keep up with a  
238 certain speed, which was set at 2-5 km/h for the majority of wheelchair ergometry test and at  
239 50-60 rpm for tests conducted with arm crank ergometry.

240 Other studies described a test protocol in which physical demands were increased by  
241 slope gradient inclination (n = 12). Most of these studies using such a protocol applied the  
242 protocol as described by Kilkens et al. (2004) (105). This protocol involves starting at a  
243 propulsion speed of 2, 3 or 4 km/h, depending on the lesion level, and increments in slope  
244 gradient of 0.36° per minute. Eight studies used a protocol similar to the protocol used in the

245 studies of Gass and colleagues (41-43). This protocol describes an increment in speed until a  
246 certain speed was reached. Subsequently, load was added or slope gradient was increased in  
247 order to increase the physical demands. One study used a speed-graded protocol (13).

248 *Intermittent maximal exercise tests.* The physical demands in all 14 intermittent test protocols  
249 were increased by increments in load per stage. The increments were mostly between 2W and  
250 10W, but two studies reported on increments of 15W per stage (78, 86). The propulsion speed  
251 was comparable to the incremental test protocols, with 3-8 km/h for tests performed in a  
252 wheelchair ergometer or hand cycle and 50-70 rpm for tests that used arm crank ergometry. In  
253 all intermittent protocols, the period of exercise was longer (2-4 min) than the period of rest  
254 (30s - 3 min). The rest period allowed for blood lactate, blood pressure and RPE  
255 measurements (14, 31, 54, 86). Two studies applied an intermittent protocol because it  
256 prevents for arm fatigue and would therefore result in higher peak aerobic values (34, 35).

257 *Constant load maximal exercise tests.* In the two studies that used wheelchair ergometry, no  
258 increments per stage were applied but participants had to propel at a maximal tolerated  
259 constant load, while keeping a speed of 4.5 or 5.5 km/h (66, 88).

260 *Submaximal exercise tests.* Two types of submaximal test protocols were identified: those  
261 with increments in physical demands (20 tests) and those without increments (8 tests). The  
262 physical demands were increased by adding load (11 tests), increasing the slope gradient with  
263  $0.36^\circ$  (7 tests), or increasing heart rate with 15 bpm or 20%HR<sub>max</sub> (2 tests). Load increments  
264 ranged from 5 to 30W, or were set at 20%PO<sub>est</sub>, 30% of Maximal Tolerated Power (MTP) or  
265 75 kpm. The number of stages varied among the submaximal tests. The protocol of six tests  
266 consisted of one stage, 11 tests applied two stages of exercise in the test protocol, seven tests  
267 included three stages and four tests consisted of five or six stages. Stage duration ranged from  
268 2 to 7 minutes and these stages of exercise were alternated with periods of 1 to 12 minutes  
269 rest in 11 of the 28 submaximal protocols.

270

271 Insert table 3.

272

### 273 **Adherence to guidelines**

274 Pre-test screening procedures were reported by 35 studies. The screening was usually  
275 performed by a physician and involved medical examination, an ECG and spirometry. Other  
276 reported procedures were conducting a health questionnaire or obtaining a medical history.  
277 Five studies referred to the ACSM guidelines and one study referred to the American  
278 Thoracic Society for pre-test screening procedures (14, 21, 32, 65, 91).

279         There were two reasons identified to terminate a maximal exercise test: when a patient  
280 becomes symptomatic and when the patient has reached maximum effort. Nineteen tests  
281 applied symptom-limited test termination criteria of which ten referred to the ACSM  
282 guidelines. The other nine tests used ECG abnormalities, blood pressure drop, dysreflexia, or  
283 adverse symptoms as criteria. Maximal effort was reported in 81 tests as termination  
284 reference, with volitional exhaustion (n = 32), unable to maintain speed or load (n = 21) or  
285 both the latter (n = 28) as criteria. Five studies did not report on termination guidelines.

286

### 287 **Adverse events**

288 Of the nine studies that reported on clinical abnormalities during maximal testing, five  
289 reported no clinical abnormalities. Three studies reported on relevant abnormalities in three  
290 patients, which included a fall in systolic blood pressure during cooling down, inability to  
291 keep up with the speed and bradycardia and hypotension after testing (37, 76, 92). For one  
292 subject,  $PO_{peak}$  could not be determined due to unknown reason (27).

293 For submaximal testing, two studies reported on adverse events, which were the  
294 inability to maintain 3 minutes of propulsion (2 persons) and mild muscle spasms during  
295 cycling (4 persons) (53, 93). One study reported no adverse events (104).

296

### 297 **Peak outcomes**

298 Thirty studies described criteria for reaching a valid  $VO_{2peak}$ . The criteria used included  
299 attainment of the age-predicted maximal heart rate (APMHR) ( $n = 16$ ), RER above a certain  
300 level ( $>1.0-1.15$ ) ( $n = 21$ ),  $VO_2$  plateau despite an increase in work rate ( $n = 17$ ) and blood  
301 lactate above a certain level ( $> 8-10$  mmol/l) ( $n = 4$ ). Four studies opted for a supra-maximal  
302 protocol in order to verify the attained peak  $VO_2$ . Other criteria were similar to the previously  
303 described termination guidelines, including exhaustion or inability to maintain speed or load  
304 ( $n = 5$ ). One study referred to the ACSM guidelines (71).

305 Approximately half of the studies ( $n = 16$ ) also reported the number of people who  
306 met the predefined criteria. The number of participants reaching a  $VO_2$  plateau was reported  
307 by eight studies, with 60% to 100% reaching the plateau. Defined criteria related to RER,  
308 APMHR and blood lactate were met by 80% to 100% of the participants.

309 Varying outcomes in  $VO_{2peak}$  were reported in the included studies. For tests  
310 performed in a wheelchair ergometer, the mean reported  $VO_{2peak}$  of all included studies was  
311 24.2 ml/kg/min with ranging values from 7.5 to 40.4 ml/kg/min. Mean value (19.21  
312 ml/kg/min) and range (8.8-38.1 ml/kg/min) were comparable for tests using arm crank  
313 ergometry or hand cycling. The lowest values were found in untrained participants with  
314 cervical lesions (25, 106), whereas the highest values were found in trained participants with a  
315 paraplegia (19, 74). Some studies reported  $VO_{2peak}$  in l/min, with values ranging from 0.55 to  
316 2.35 l/min (13, 24).

317 The majority of  $PO_{peak}$  outcomes was expressed in Watts with a mean  $PO_{peak}$  of 56.4W  
318 (11-210W) for wheelchair ergometry tests and 66.5W (15-159W) for tests using arm crank  
319 ergometry or hand cycling. The lowest reported value was 11W, found in a group of  
320 participants with high cervical lesions (24). The highest reported  $PO_{peak}$  was 210W, found in  
321 the same group of participants that reported the highest  $VO_{2peak}$  value using wheelchair  
322 ergometry (74). Other reported outcome measures for  $PO_{peak}$  were W/kg (0.15-1.11 W/kg),  
323 kgm/min (255-653 kgm/min) and kpm/min (141-761 kpm/min) (25, 34, 35, 61, 63, 98). The  
324 mean and ranging values for RER and  $HR_{peak}$  were 1.19 (0.92-1.44) and 155 bpm (96-198  
325 bpm), respectively.

326

### 327 **Submaximal outcomes**

328 Reported submaximal  $VO_2$  means ranged from 9.3-13.1 ml/kg/min and 0.74-1.90 l/min, with  
329 overall mean values of 11.2 ml/kg/min and 1.16 l/min respectively. Mean  $PO$ , RER and HR  
330 values were 46.0W (17.7-78.4W), 0.92 (0.88-0.96) and 116 bpm (97-166 bpm), respectively.

331

## 332 **DISCUSSION**

333

334 The aim of this systematic review was to summarize the available maximal and submaximal  
335 aerobic exercise tests for wheelchair-dependent persons with a SCI. The identified exercise  
336 tests showed a large variety in population characteristics, exercise modes, testing protocols  
337 and outcome measures. Limited studies reported on adherence to recommendations, adverse  
338 events and oxygen uptake validation. Possible useful applications of the available maximal  
339 and submaximal aerobic exercise tests for clinical SCI rehabilitation will be discussed.

340

341 **Exercise mode**

342 Arm crank ergometry and wheelchair ergometry were the most commonly used exercise  
343 modes among the included studies.  $PO_{peak}$  and  $VO_{2peak}$  comparisons between both modalities  
344 showed no difference in  $VO_{2peak}$ , but a somewhat higher  $PO_{peak}$  for arm crank ergometry. This  
345 is in line with previous studies in which a group of persons with a paraplegia performed a  
346 maximal exercise test in both modes (76, 107). Additionally, two studies that only compared  
347  $VO_{2peak}$  outcomes for both modes reported no differences in  $VO_{2peak}$  as well (44, 77).  
348 Although no adverse events of musculoskeletal problems were reported, previous literature  
349 indicated that wheelchair ergometry was usually more straining to the musculoskeletal system  
350 than arm crank ergometry and hand cycling. Wheelchair ergometry puts the participant to a  
351 higher risk for over-use problems of the upper-extremities (29, 76, 108, 109). On the contrary,  
352 wheelchair ergometry has excellent application opportunities for submaximal testing in SCI  
353 rehabilitation, since it provides relevant data of wheelchair performance and mobility in daily  
354 life (110). Exercise modes that are more suitable for maximal exercise testing in clinical  
355 rehabilitation are arm crank ergometry and hand cycling. Both modes allow for continuous  
356 force application and no peak loads occur during propulsion. The hand cycle mode was found  
357 to be highly relevant for training and testing the peak cardiovascular capacity and fitness  
358 during rehabilitation, and it was demonstrated that exercise intensities as prescribed by the  
359 ACSM guidelines could be attained (29, 92, 111). Notwithstanding, further research is  
360 necessary on how hand cycling can be optimally used for training and testing in the SCI  
361 rehabilitation setting (112, 113).

362         The final choice of equipment depends on the goal of the test and of the participants'  
363 ability. For example, when designing a test for rehabilitants, the arm crank ergometer and  
364 hand cycle are recommended for determining peak physical capacities during maximal

365 exercise testing, whereas the more task-specific hand-rim wheelchair propulsion has a higher  
366 relevance for submaximal testing and assessing daily life performance (110).

367

### 368 **Test protocols**

369 In order to attain the peak physical abilities during an aerobic maximal exercise test, it is  
370 important to determine the increments per stage carefully. This is especially true for those  
371 who are rehabilitating from a SCI, since these people are often vulnerable and sensitive to  
372 overuse problems (27, 114, 115). When large increments per stage are applied, the  
373 relationship between oxygen uptake and workload is usually weaker. Therefore, it is  
374 recommended to use small to modest individualized increments per stage, resulting in  
375 completion of the test between 8 and 12 minutes (7, 116). The results revealed two common  
376 ways of increasing the physical demands during incremental testing. One way is to add  
377 resistance each stage (5W-10W), with lower amounts of resistance increments for those with  
378 a high lesion level. Another option is to increase the slope gradient per stage ( $0.36^\circ$ ), while  
379 fixing the belt velocity at a certain speed (2 or 3 or 4 km/h) depending on the physical  
380 capacity of the patient. The duration of the stage should be between 60s and 120s. Both  
381 protocol types seem to be feasible and can be executed with any exercise mode. However, one  
382 should take into account that performing a maximal exercise test has some practical  
383 limitations for clinical rehabilitation. For example, if the slope gradient is getting too steep  
384 during testing, the patient could be forced to quit because of muscular failure rather than  
385 cardiovascular failure. A sudden termination of the test could cause the patient to roll  
386 backwards on the treadmill. When opting for increasing the resistance by using a pulley  
387 system, instead of increasing the slope gradient, these practical limitations do not apply. In  
388 fact, the posture of the patient does not change while using a pulley system to increase the  
389 physical demands and this system allows for a larger variety in increments per stage. Because



390 of these practical advantages, it would be preferred to opt for increasing the resistance by  
391 using a pulley system in a clinical rehabilitation setting, rather than increasing the slope  
392 gradient of the treadmill.

393

#### 394 **Adherence to guidelines**

395 In previous review studies it was found that exercise testing in patient groups does not always  
396 comply with exercise testing guidelines (117, 118). This is line with the findings of the  
397 present review, in which only five studies referred to the common accepted ACSM guidelines  
398 for exercise testing. These guidelines recommend pre-test screening for identifying  
399 contraindications for maximal exercise and it is obvious that all participants should have a  
400 pre-test screening. A pre-test screening was, however, reported in only 35 of 95 of the  
401 included studies in the current review. In the future, inclusion- and exclusion criteria should  
402 be clearly described, pre-test screening should be performed and participants should be  
403 monitored during the test. Approval of the involved physician, responsible for the treatment,  
404 should be an additional criterion for SCI patients. Test termination criteria used in the  
405 included studies were all in accordance with ACSM guidelines.

406 For participants who cannot sustain incremental exercise due to safety reasons of  
407 physical limitations, it is recommended to conduct an intermittent test protocol. Such a  
408 protocol allows for the prevention of muscle fatigue, but also for monitoring blood pressure  
409 measurement (14). In case intermittent exercise is not feasible either, the maximal aerobic  
410 capacity can be estimated from submaximal testing outcomes (110).

411

#### 412 **Reporting outcomes**

413 The reported peak values are difficult to interpret, since 30 studies described criteria for  
414 reaching a valid peak oxygen uptake. Of these 30 studies, only 16 studies reported the number  
415 of participants who satisfied these criteria. The primary criterion for  $VO_{2peak}$  is the  
416 achievement of a  $VO_2$  plateau despite an increase in work rate (7, 119). The use of this  
417 criterion is, however, questionable, since more than one plateau can be achieved during  
418 incremental exercise or the plateau cannot be found (119-121). In case a  $VO_2$  plateau could  
419 not be determined, Edvardsen et al. (2014) recommend the use of an RER cut-off value ( $>1.0-$   
420  $1.15$ ) as criterion for attaining  $VO_{2peak}$  (119). This recommendation is in line with findings of  
421 the current review.

422 Several studies used the attainment of the APMHR as a criterion for maximal effort,  
423 but the use of this criterion in the SCI population is questionable, since the sympathetic  
424 innervation of the heart derives from T1 to T4. Persons with a lesion at or above T4 might  
425 show a non-linear relation between HR and  $VO_2$  (84, 89). The attainment of APMHR is  
426 therefore not recommended as a criterion for attaining a valid  $VO_2$ .

427 There are currently no guidelines available for reporting outcomes of exercise testing  
428 for any clinical population (117). It is, however, recommended to report peak oxygen uptake  
429 and power output values, since these two parameters were identified as primary outcome  
430 measure in a previous literature study regarding persons with a SCI. Furthermore, it is  
431 recommended to report on  $VO_2$  plateau and mean RER measures (116, 118). Additionally, in  
432 order to enhance comparability of clinical rehabilitation outcomes, the criteria and reasons for  
433 test termination should be reported and results need to be compared with norm scores for  
434 persons with a paraplegia and tetraplegia.

435

436 **Implications for rehabilitation**

- 437 • Regularly testing the cardiovascular capacity during SCI rehabilitation will enable us  
438 to monitor the impact of rehabilitation interventions on an individual level.
- 439 • The incremental arm ergometry test with small increments per stage is most relevant  
440 for the assessment of the peak cardiovascular capacity.
- 441 • For the assessment of daily life functioning, the submaximal wheelchair ergometer test  
442 is preferable.
- 443 • Hand cycling is a promising exercise mode for both testing and training.
- 444 • Systematically reporting on test termination, criteria for attaining valid peak outcomes  
445 and adverse events is necessary to enhance comparability of results.

446

#### 447 **Limitations and recommendations**

448 A few limitations need to be taken into account when interpreting the results of the current  
449 review. First of all, it might be possible that some studies using an aerobic exercise test in the  
450 SCI population have been missed, even though a comprehensive search was conducted. We  
451 are however confident that the results and conclusions are representative, given the large  
452 number of 95 included studies. A disadvantageous effect of the broad inclusion strategy,  
453 however, is the wide diversity found regarding study methods and populations, which makes  
454 it more difficult to draw conclusion. At the same time, this latter issue is contradicted by the  
455 fact that persons with a SCI with all kinds of fitness levels, from rehabilitant to athlete, are  
456 represented in the current study.

457 The current review provides some guidance for creating an evidence-based  
458 standardized aerobic exercise test, but it should be noted that measuring peak  
459 cardiorespiratory abilities is only one part of the total physical capacity when referring to the  
460 ACSM definition of physical fitness. The ACSM identified several components of physical

461 fitness in addition to cardiorespiratory fitness, namely body composition, flexibility, muscular  
462 strength and muscular endurance (7). In order to attain a full understanding of a patients'  
463 physical capacity, it is necessary to measure these other components as well (6).

464 An important factor for research in the context of using exercise testing as a means of  
465 evaluating training or active lifestyle interventions is the use of a control group in the study  
466 design. In only 12 of the 68 studies in the present review, of which two studies were a  
467 randomized controlled trial, a control group was included. Although establishing a control  
468 group is often complicated in SCI research due to the absence of an unlimited source of  
469 persons with a SCI and the existing heterogeneity in this population, it should be encouraged  
470 to establish larger subject groups, and thus statistical power, in future studies. A possibility  
471 could be conducting structured training and testing programs in able-bodied persons, since  
472 their physiological stress and strain appears to be comparable for those with a paraplegia  
473 (112). Furthermore, by introducing multicenter collaboration, outcomes of various training  
474 and testing procedures can be evaluated systematically in a homogeneous group as well (6).  
475 Another option is to perform a multilevel analysis to compare groups of patients with SCI.  
476 This statistical analysis technique, that was applied in a recent longitudinal cohort study on  
477 physical activity behavior in patients, allows for missing values and can correct for  
478 differences at the level of rehabilitation center (122).

479 The current review showed various opportunities for the application of exercise testing  
480 in SCI rehabilitation. However, the findings did not enable us to describe the most preferable  
481 test protocol for maximal and submaximal testing. Future research should therefore focus on  
482 validating the different exercise modes. Furthermore, practical limitations should be  
483 considered and consensus regarding reporting outcomes needs to be achieved.

484

485 **CONCLUSION**

486

487 This systematic review can be seen as a first step in the development of a standardized aerobic  
488 exercise test for daily SCI rehabilitation practice. An extensive variety in population  
489 characteristics, exercise modes, testing protocols and outcome measures was revealed.  
490 Limited studies reported on adherence to recommendations, adverse events and oxygen  
491 uptake validation. An incremental test protocol with small, individualized increments per  
492 stage seems preferable, but additional validation of the exercise modes is required to draw  
493 definitive conclusions. Submaximal testing is relevant for assessing the performance at daily  
494 life intensities and for estimating  $VO_{2peak}$ . Furthermore, consensus regarding reporting test  
495 procedures and outcomes needs to be achieved to enhance comparability of rehabilitation  
496 results.

497

#### 498 **DECLARATION OF INTEREST**

499

500 We can confirm that there are no known conflicts of interest associated with this publication  
501 and there has been no significant financial support for this work that could have influenced  
502 this outcome. The manuscript has been read and approved by all named authors.

503

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