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Peak oxygen uptake measured during a perceptually-regulated exercise test is reliable in community-based manual wheelchair users

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16

17 **Abstract**

18 This study aimed to compare test-retest reliability and peak exercise responses from
19 ramp-incremented (RAMP) and maximal perceptually-regulated (PRET_{max}) exercise
20 tests during arm crank exercise in individuals reliant on manual wheelchair
21 propulsion (MWP). Ten untrained participants (9 male) completed four trials over a
22 2-week period, performing two RAMP (0-40 W + 5-10 W·min⁻¹) trials one week
23 followed by two PRET_{max} trials the next, or vice versa. PRET_{max} consisted of five, 2-
24 min stages performed at Ratings of Perceived Exertion (RPE) 11, 13, 15, 17 and 20.
25 Participants freely changed the power output to match the required RPE. Gas
26 exchange variables, heart rate, power output, RPE and affect were determined
27 throughout trials. The $\dot{V}O_{2peak}$ from RAMP (14.8 ± 5.5 ml·kg⁻¹·min⁻¹) and PRET_{max}
28 (13.9 ± 5.2 ml·kg⁻¹·min⁻¹) trials were not different ($P = 0.08$). Measurement error
29 was 1.7 and 2.2 ml·kg⁻¹·min⁻¹ and coefficient of variation 5.9% and 8.1% for
30 measuring $\dot{V}O_{2peak}$ from RAMP and PRET_{max}, respectively. Affect was more
31 positive at RPE 13 ($P = 0.02$), 15 ($P = 0.01$) and 17 ($P = 0.01$) during PRET_{max}. This
32 study shows the PRET_{max} can be used to measure $\dot{V}O_{2peak}$ in participants reliant on
33 MWP and leads to a more positive affective response compared to RAMP.

34 **Key words:** oxygen consumption; RPE; disability; exercise testing; test-retest
35 reliability

36 **Introduction**

37 Important determinants of physical capacity in individuals dependant on manual
38 wheelchair propulsion (MWP) include unmodifiable factors, such as age, gender and
39 type of disability. Yet sports participation (Janssen, Dallmeijer, Veeger, & van der
40 Woude, 2002) and exercise training (Hicks et al., 2011; Valent, Dallmeijer, Houdijk,
41 Talsma, & van der Woude, 2007) can positively affect physical capacity in persons
42 reliant on MWP. Furthermore, increased physical capacity, as measured using peak
43 oxygen uptake ($\dot{V}O_{2peak}$) is linked with improved physical functional status
44 (Dallmeijer & van der Woude, 2001), life satisfaction (van Koppenhagen et al., 2014)
45 and self-independency during activities of daily living (Hjeltne & Jansen, 1990) in
46 this population. Considering these known benefits of increased $\dot{V}O_{2peak}$, as well as
47 increasing life expectancy for people reliant on MWP (Middleton et al., 2012; Savic
48 et al., 2017), there is a need for appropriate protocols with which to measure $\dot{V}O_{2peak}$.

49 Traditionally, ramp-incremented (RAMP) tests which feature fixed increases
50 in power output (PO) that continue until volitional exhaustion (Whipp, Davis, Torres,
51 & Wasserman, 1981) have been adopted for both able-bodied and disability groups.
52 However, despite a RAMP protocol being the most common method for the direct
53 measurement of $\dot{V}O_{2peak}$, this form of exercise testing has, in recent years, been
54 subject to criticism in that it is ‘open loop’ in nature, i.e., it has no predetermined or
55 known end-point, and therefore does not allow for pacing to occur (Noakes, 2008).
56 An alternative to RAMP testing which is gaining in popularity in the scientific
57 literature, and recently described as a paradigm shift in exercise testing methodology
58 (Beltz et al., 2016) is to progress the intensity based on incremental clamping of the
59 Ratings of Perceived Exertion (RPE), as opposed to PO.

60 Research has validated the use of a maximal perceptually-regulated exercise
61 test (PRET_{max}) to measure $\dot{V}O_{2peak}$ during cycle (Straub, Midgley, Zavorsky, &
62 Hillman, 2014) and handcycle exercise (Hutchinson, Paulson, Eston, & Goosey-
63 Tolfrey, 2017) against RAMP protocols. However, the PRET_{max} method has yet to
64 be applied to participants reliant on MWP for daily activity. The PRET_{max} consists of
65 five 2-min stages clamped at RPE 11, 13, 15, 17 and 20 on Borg's 6-20 RPE scale
66 (Borg, 1998). Importantly, the PRET_{max} is of fixed duration and allows the
67 participant to control the workload and pacing strategy, satisfying the major
68 criticisms of the RAMP protocol.

69 The use of PRET_{max} in exercise testing of participants reliant on MWP may
70 be justified when considering the affective response to exercise. Previous research in
71 able-bodied participants has shown that exercise at a self-selected intensity, as in the
72 PRET_{max}, leads to a more positive affective response compared to imposed exercise
73 of the same intensity, as in the RAMP (Evans, Parfitt, & Eston, 2014; Hamlyn-
74 Williams, Freeman, & Parfitt, 2014; Rose & Parfitt, 2007) Hence, the PRET_{max} may
75 be a preferred option to use instead of RAMP, particularly for older participants, or
76 those who are beginning to become more physically active.

77 This is the first study to investigate the use of a PRET_{max} in a population with
78 a disability. The aim of this study was to assess the reliability of the PRET_{max} to
79 measure peak exercise responses in participants reliant on MWP and to compare the
80 responses between PRET_{max} and RAMP. A further aim was to investigate the
81 affective response to PRET_{max} and RAMP protocols. It was hypothesised that the
82 PRET_{max} and RAMP would produce similar maximal exercise responses, and that
83 affect would be more positive during PRET_{max} than RAMP.

84 **Methods**

85 ***Participants***

86 Ten (9 male, 1 female), sedentary or recreationally active MWP participants gave
87 written informed consent to participate in this study, which was approved by the
88 Hamilton Health Sciences Integrated Research Ethics Board (Ref. #1615).
89 Descriptive characteristics are presented in Table 1, which represent a group typical
90 of that commencing an exercise program as part of the Physical Activity Centre of
91 Excellence at McMaster university. Participants were deemed safe and appropriate to
92 take part in this study as a result of being cleared by a physician prior to joining the
93 exercise program. This included having completed a maximal exercise test.

94 ****Table 1 near here****

95 ***Experimental design***

96 Following a randomised, crossover design, participants completed four maximal
97 exercise tests over a two-week period (Figure 1) while seated in their everyday
98 wheelchair. Trials were separated by 48 to 96 hours. All testing was conducted using
99 the same wall-mounted electrically braked arm crank ergometer (Lode Angio, Lode
100 B. V., Groningen, Netherlands) operating asynchronously. The ergometer was
101 adjusted so that the centre of the crank axis was level with the shoulder and so there
102 was slight elbow flexion at the furthest point of the crank cycle.

103 ****Figure 1 near here****

104 All trials were performed at the same time of day within each participant to
105 minimise diurnal variations (Hill, Cureton, & Collins, 1989) and dietary intake was
106 replicated in the 24 hours before all trials. Participants refrained from alcohol
107 consumption and vigorous exercise for 24 hours, and caffeine for 6 hours preceding

each trial. Participants preferred cadence was established in the warm-up to their first trial, when they were invited to experiment with various cadences and choose what they preferred. This cadence was then recorded and subsequently participants were asked to maintain it at that level for the maximal trials.

Ramp-incremented $\dot{V}O_{2peak}$ test (RAMP) and verification stage (VER)

The RAMP started at 0-40 W and was increased by 5-10 W·min⁻¹ until volitional exhaustion or preferred cadence could not be maintained. Starting PO and the PO increment were individualised for participants to match the RAMP test duration to that of the PRET_{max} (10 min). Gas exchange variables were collected throughout using a facemask (7450 Series V2, Hans Rudolph Inc., Shawnee, USA) and online gas analysis system (Moxus Metabolic System, AEI Technologies Inc., Pittsburgh, USA). Heart rate (HR) was assessed throughout (RS400, Polar, Kempele, Finland) and differentiated measures of peripheral (RPE_P), central (RPE_C) and overall (RPE_O) RPE (Borg, 1998) as well as Feeling Scale (FS) rating (Hardy & Rejeski, 1989) were verbally recalled in the final 15 s of each stage. The FS ranges from +5 (very good) to -5 (very bad) with anchors at +3 (good), +1 (fairly good), 0 (neutral), -1 (fairly bad) and -3 (bad). Prior to all trials participants were read standardised instructions on the use of Borg's 6-20 RPE scale (Borg, 1998).

Following termination of the RAMP participants completed 10 min of recovery (unloaded arm cranking and/or seated rest) before performing the verification phase (VER). PO was increased by 5 W from the end of the RAMP and participants cranked again until volitional exhaustion or cadence could not be maintained. Gas exchange variables, HR and subjective measures were recorded as during RAMP. Throughout RAMP and VER participants maintained their preferred

132 cadence, which along with the subjective scales, was the only information visible to
133 participants.

134 ***Perceptually regulated $\dot{V}O_{2peak}$ test ($PRET_{max}$)***

135 During $PRET_{max}$ participants completed five, two-minute stages where RPE_O was
136 clamped and progressively increased with each stage. Stages corresponded to RPE
137 11, 13, 15, 17 and 20 on Borg's 6-20 RPE scale (Borg, 1998). Participants self-
138 regulated the PO by saying "up" or "down", where the investigator would adjust the
139 PO by 3 W accordingly. Participants were not aware of the magnitude of the change
140 but were instructed to change PO as often as required to maintain the desired RPE
141 and to reach maximal exertion at the end of the final stage. As with during RAMP,
142 participants maintained their preferred cadence throughout and had cadence along
143 with subjective scales in their line of sight. Elapsed time was also visible during
144 $PRET_{max}$ to allow pacing in relation to the end point of the exercise bout. $\dot{V}O_2$, HR
145 and subjective measures were recorded as they were during RAMP.

146 ***Data Processing and Statistical Analysis***

147 Analysis was performed using IBM SPSS Statistics 22 (SPSS Inc., Chicago, IL.).
148 Physiological data are presented as mean $\pm$ SD, whilst subjective data are presented
149 as median (interquartile range). Statistical significance was accepted at $P < 0.05$. For
150 all tests HR and gas exchange variables were subjected to a 30 s rolling average with
151 the highest value taken as the peak response. During $PRET_{max}$ PO was also subjected
152 to a 30 s rolling average with the highest value taken as the peak PO (PO_{peak}). For
153 RAMP trials PO_{peak} was calculated based on the final completed stage and proportion
154 of the next stage completed using the formula:

$$155 \quad PO_{peak} = F + \left(\left(\frac{t}{60s} \right) \times I \right).$$

156 Where F = PO of the final completed stage, t = time spent in the final, uncompleted
157 stage in seconds, 60 s = stage duration and I = the PO increment. In keeping with the
158 assessment of maximal exercise responses, the greater responses for RAMP and
159 PRET_{max} from repeat tests were used in subsequent analysis.

160 Reliability of peak physiological variables was assessed by calculating the
161 coefficient of variation, and the intraclass correlation coefficient ($\text{ICC}_{3,1}$) using an
162 openly available spreadsheet (Hopkins, 2015). The $\text{ICC}_{3,1}$ were interpreted for their
163 magnitude in accordance with Munro's criteria where 0-0.25 is "little to no"
164 correlation, 0.26-0.49 "low" correlation, 0.50-0.69 "moderate" correlation, 0.70-0.89
165 "high correlation" and 0.90-1.00 "very high" correlation (Plichta, Kelvin, & Munro,
166 2013). Furthermore, measurement error (ME) was calculated as the within-subject
167 standard deviation and the smallest detectable difference (SDD) as 2.77 multiplied
168 by ME (Bland & Altman, 1996).

169 Data were checked for normal distribution using the Shapiro-Wilk test
170 statistic. Familiarisation with peak exercise testing across trial 1 to 4 was
171 investigated using one-way repeated measures Analysis of Variance (ANOVA).
172 Differences in test duration and peak physiological responses between protocols
173 were assessed via paired samples t-test and for maximal subjective responses using
174 Wilcoxon Signed Rank test. Bland-Altman plots with 95% limits of agreement (LoA)
175 were produced to assess the agreement for $\dot{V}\text{O}_{2\text{peak}}$, HR_{peak} and peak respiratory
176 exchange ratio (RER_{peak}) between the two protocols (Bland & Altman, 1999).

177 Individual $\text{RPE}:\dot{V}\text{O}_2$, $\text{RPE}:\text{HR}$ and $\text{RPE}:\text{PO}$ linear relationships were
178 determined for RPE_P , RPE_C and RPE_O during RAMP and PRET_{max} . These
179 relationships underwent a Fisher transformation to allow the calculation of group

averages. Differences in group correlations were assessed by two-way Analysis of Variance (ANOVA), with repeated measures on protocol (RAMP x PRET_{max}) and mode of RPE (RPE_P x RPE_C x RPE_O). FS ratings were extracted from the RAMP and PRET_{max} corresponding to RPE 11, 13, 15 and 17, or by interpolation if the specific RPE was not reported. Wilcoxon Signed Rank test was then used to assess difference in FS rating between protocols at each RPE value.

A priori power analysis was conducted in G*Power 3.1 using the test-retest reliability statistics for absolute $\dot{V}O_{2peak}$ from a previous study involving individuals with a spinal cord injury performing wheelchair ergometry (Leicht, Tolfrey, Lenton, Bishop, & Goosey-Tolfrey, 2013). For statistical power of 0.80 and α equal to 5%, it was deemed that 10 participants would be required to find a significant difference between RAMP and PRET_{max}.

Results

Each participant completed all four trials and there were no missing data points. ANOVA revealed no learning effect as no significant differences were found across trial one to trial four for absolute $\dot{V}O_{2peak}$ ($F_{2,1} = 0.343$, $P = 0.73$), relative $\dot{V}O_{2peak}$ ($F_{2,1} = 0.402$, $P = 0.65$), HR_{peak} ($F_{1,5} = 2.314$, $P = 0.14$) or PO_{peak} ($F_{1,7} = 0.328$, $P = 0.69$). There was no significant difference between RAMP and VER for absolute $\dot{V}O_{2peak}$ (1.3 ± 0.3 versus 1.3 ± 0.3 L·min⁻¹, $t_{17} = -0.441$, $P = 0.67$), relative $\dot{V}O_{2peak}$ (14.1 ± 4.3 versus 14.7 ± 4.7 ml·kg⁻¹·min⁻¹, $t_{17} = -0.747$, $P = 0.47$) or HR_{peak} (139 ± 27 versus 135 ± 27 beats·min⁻¹, $t_{18} = 1.108$, $P = 0.28$).

201 **Reliability**

202 Test-retest reliability for peak physiological variables obtained from RAMP and
203 PRET_{max} are shown in Table 2. The ICC_{3,1} was classified as “very high” for absolute
204 and relative $\dot{V}O_{2\text{peak}}$, HR_{peak}, PO_{peak} and RER_{peak} for both RAMP and PRET_{max}.

205 ****Table 2 near here****

206 **Agreement between protocols**

207 Peak responses for RAMP and PRET_{max} are presented in Table 3. The Pearson
208 correlation between responses from RAMP and PRET_{max} was $r = 0.922$ ($P < 0.05$)
209 and $r = 0.969$ ($P < 0.05$) for absolute and relative $\dot{V}O_{2\text{peak}}$, respectively. Bland-
210 Altman plots with 95% LoA for absolute and relative $\dot{V}O_{2\text{peak}}$, HR_{peak} and RER_{peak}
211 are displayed in Fig. 2.

212 ****Table 3 near here****

213 ****Figure 2 near here****

214 Group averaged correlations are shown in Table 4. For the RPE: $\dot{V}O_2$
215 relationship there was no effect of protocol ($F_{(1,0)} = 0.002$, $P = 0.96$) or mode of RPE
216 ($F_{(1,1)} = 0.127$, $P = 0.75$). Similarly for RPE:HR there was no effect of protocol ($F_{(1,0)} =$
217 0.150 , $P = 0.71$) or mode of RPE ($F_{(1,4)} = 1.362$, $P = 0.28$). For the RPE:PO
218 relationship there was a significant effect of protocol ($F_{(1,0)} = 8.025$, $P = 0.02$), with
219 Bonferroni post-hoc comparison showing that the relationship was stronger in
220 RAMP compared to PRET_{max}. There was no effect of mode of RPE on the RPE:PO
221 relationship ($F_{(1,2)} = 0.968$, $P = 0.36$).

222 ****Table 4 near here****

223 *Affective response*

224 The peak FS rating was significantly smaller during RAMP ($Z = -2.368$, $P = 0.02$)
225 compared to PRET_{max} (Table 2). There was no significant difference in average FS
226 rating between protocols ($Z = -1.265$, $P = 0.21$). At submaximal RPE values, affect
227 was significantly more positive during PRET_{max} compared to RAMP at RPE 13 ($Z =$
228 -2.403 , $P = 0.02$), 15 ($Z = -2.539$, $P = 0.01$) and 17 ($Z = -2.527$, $P = 0.01$), see Table
229 5.

230 *****Table 5 near here*****

231 **Discussion**

232 The main finding of this study was that there was no significant difference in $\dot{\text{V}}\text{O}_{2\text{peak}}$
233 between RAMP and PRET_{max} . Furthermore, the measurement error (ME) for
234 measuring $\dot{\text{V}}\text{O}_{2\text{peak}}$ using PRET_{max} or RAMP was greater than the mean difference in
235 $\dot{\text{V}}\text{O}_{2\text{peak}}$ between protocols. Therefore, these findings support the use of PRET_{max} for
236 measuring $\dot{\text{V}}\text{O}_{2\text{peak}}$ in participants reliant on MWP. The finding of similar $\dot{\text{V}}\text{O}_{2\text{peak}}$
237 values between PRET_{max} and RAMP corroborates findings from research involving
238 able-bodied participants performing lower (Chidnok et al., 2013; Evans et al., 2014;
239 Hanson et al., 2016; Hanson, Reid, Cornwell, Lee, & Scheadler, 2017; Lim,
240 Lambrick, Mauger, Woolley, & Faulkner, 2016; Straub et al., 2014) and upper
241 (Hutchinson et al., 2017) body exercise. Importantly, the results of the current study
242 provide support for the use of the PRET_{max} in participants reliant on MWP.

243 This support for the use of PRET_{max} comes from the finding of more positive
244 affect during the PRET_{max} compared to RAMP. This finding in participants reliant
245 on MWP corroborates previous research using able-bodied participants performing
246 recumbent cycle ergometry (Evans et al., 2014). The affect experienced during

247 exercise could be a particularly important consideration when working with
248 participants who have low habitual levels of physical activity, or who are
249 unaccustomed to maximal exercise. This is based on evidence showing that affect
250 during exercise predicted physical activity participation 6 to 12 months later in
251 previously sedentary individuals (Williams et al., 2008). With the suggestion that
252 more positive feelings during exercise can aid with adherence to a long-term exercise
253 intervention, there are thus growing calls for the role of the affective response to
254 receive greater consideration in exercise prescription guidelines (Ekkekakis, Parfitt,
255 & Petruzzello, 2011; Williams, 2008). The current results would also support the
256 consideration of affective response when selecting a maximal exercise test protocol.

257 This is the first study in this population group to challenge the traditional use
258 of maximal incremental tests using fixed PO stages. The results also strengthen the
259 case for obtaining a direct measurement of $\dot{V}O_{2peak}$ in contrast to predicting it from
260 the $\dot{V}O_2$ at submaximal RPE, although only when maximal exercise testing is
261 deemed safe and appropriate. Concerns over exacerbating the risk of shoulder injury,
262 peripheral fatigue and autonomic dysfunction during maximal exercise has led to
263 questions of whether maximal testing is appropriate in populations reliant on MWP
264 (Totossy de Zepetnek, Au, Hol, Eng, & MacDonald, 2016). If though, as was the case
265 in this study, maximal exercise is deemed safe then a direct measurement of $\dot{V}O_{2peak}$
266 should be made.

267 Previous studies have predicted $\dot{V}O_{2peak}$ from the submaximal $\dot{V}O_2$ during
268 single-stage fixed PO (Totossy de Zepetnek et al., 2016), incremental fixed PO (Al-
269 Rahamneh & Eston, 2011a; Al-Rahamneh et al., 2011; Goosey-Tolfrey et al., 2014)
270 testing, and a submaximal PRET (Al-Rahamneh & Eston, 2011b). However mean
271 difference (lower to upper limits of agreement) have been reported as 0 (-8 to 8)

272 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Al-Rahamneh & Eston, 2011a), 0.02 (-6.67 to 6.64) $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$
273 (Totosy de Zepetnek et al., 2016), 0.4 (-5.3 to 6.1) $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Al-Rahamneh &
274 Eston, 2011b) and 1 (-8 to 10) $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ (Al-Rahamneh et al., 2011) for various
275 prediction models compared to 0.9 (-1.8 to 3.5) $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ as found in this study
276 when comparing the PRET_{max} and RAMP. These results show increased random
277 error in the prediction models compared to the direct measurement from the
278 PRET_{max} . Greater random error increases the possibility of a prediction that either
279 under-, or over-, estimates $\dot{\text{V}}\text{O}_{2\text{peak}}$. These findings ultimately support the direct
280 measurement of $\dot{\text{V}}\text{O}_{2\text{peak}}$ when possible, with the current study supporting the
281 PRET_{max} over a traditional RAMP.

282 In addition to the new knowledge around using RPE to prescribe the intensity
283 during exercise testing for participants reliant on MWP, this study also adds support
284 to the area of RPE-based exercise prescription for this population. The cost of
285 equipment and technical expertise required for measuring $\dot{\text{V}}\text{O}_2$ and PO limit their use
286 for informing exercise intensity away from a controlled laboratory setting. As such,
287 individuals reliant on MWP have limited accessible methods for regulating exercise
288 training intensity. It has been reported that there is currently insufficient evidence to
289 support the regular use of subjective measures, such as RPE, to control intensity in
290 adults with spinal cord injury (van der Scheer, Hutchinson, Paulson, Martin Ginis, &
291 Goosey-Tolfrey, 2017). The present findings of comparable $\dot{\text{V}}\text{O}_{2\text{peak}}$ as well as
292 $\text{RPE}:\dot{\text{V}}\text{O}_2$ and $\text{RPE}:\text{HR}$ relationships between RAMP and PRET_{max} protocols suggest
293 that RPE may be used as a valid, cost effective and easily applicable means of
294 prescribing exercise intensity in participants reliant on MWP. However as this study
295 only investigates this using group-averaged single test relationships, further studies

296 need to use a higher quality, estimation versus production study design to study this
297 (van der Scheer et al., 2017).

298 A limitation of this study could be the sample size of 10 participants of a
299 heterogeneous nature in terms of their mixed impairments, differing levels of
300 cardiorespiratory fitness and habitual physical activity. Yet, despite the large inter-
301 individual variation the findings showed that PRET_{max} can be used to measure
302 $\dot{\text{V}}\text{O}_{2\text{peak}}$ in persons reliant on MWP. Furthermore, while the participants had
303 undertaken arm crank ergometry exercise before, several were unfamiliar with both
304 the specific protocols (PRET_{max} and RAMP), and indeed maximal exercise itself.
305 This may have limited their ability to push themselves to achieve the intensity
306 required (i.e. particularly for the PRET_{max} final RPE 20 stage). This potentially
307 manifested itself since the median RPE reported was 19 during this required RPE 20
308 stage of the test. The inability for these participants to apparently reach RPE 20
309 during the PRET_{max} , despite doing so in the RAMP, could serve to limit the $\dot{\text{V}}\text{O}_{2\text{peak}}$
310 values measured. Remarkably though, even with the difference in peak RPE reported
311 between PRET_{max} and RAMP, the $\dot{\text{V}}\text{O}_{2\text{peak}}$ values were shown to agree.

312 **Conclusions**

313 This is the first study to show that the PRET_{max} can be used to reliably measure
314 $\dot{\text{V}}\text{O}_{2\text{peak}}$ in participants reliant on MWP. Given the significantly more positive affect
315 felt during the PRET_{max} compared to RAMP, this study provides a compelling and
316 convincing case for the use of the PRET_{max} over RAMP in this population. The
317 PRET_{max} should be considered particularly when participants may be unaccustomed
318 with maximal exercise and when the maximal exercise assessment is one of the first
319 steps in prescribing a personalised exercise programme.

320

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444

445 **Figure captions**

446 Figure 1: Schematic of the experimental design used. Participants either performed ramp-
447 incremented (RAMP) and verification (VER) trials in week 1 (dashed lines) followed by
448 maximal perceptually-regulated exercise test (PRET_{max}) trials in week 2, or PRET_{max} in week
449 1 (solid lines) followed by RAMP and VER in week 2.

450 Figure 2: Bland-Altman plots showing 95% LoA for a) absolute $\dot{V}O_{2peak}$, b) relative $\dot{V}O_{2peak}$,
451 c) HR_{peak} and d) PO_{peak}. Mean difference between RAMP and PRET_{max} trials is indicated by
452 solid black line with upper and lower limits indicated by dotted lines.

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457 Table 1: Participant characteristics

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Participant number	Gender	PAL (h·week ⁻¹)	Age (years)	Height (cm)	Body mass (kg)	Impairment	NLI	ASIA classification	TSI (years)
1	M	5	59	185	138.0	SCI	C4 (INC)	D	14
2	M	10	69	182	122.0	SCI	C5 (INC)	D	5
3	M	0	42	165	65.9	SCI	T5 (COMP)	A	17
4	M	5	75	178	92.4	SCI	T12 (INC)	D	10
5	M	0	49	170	61.6	SCI	L1 (INC)	D	11
6	M	0	57	193	90.6	SCI	L1 (INC)	D	18
7	M	5	63	183	87.5	MS			
8	M	10	50	178	91.1	MS			
9	M	6	60	190	107.0	MS			
10	F	4	48	145	85.0	Spina Bifida			
Mean		4	57	177	94.1				12
SD		4	10	14	23.3				5

473 ASIA: American Spinal Injury Association; COMP: complete; INC: incomplete; MS: multiple sclerosis; NLI: Neurological Level of Injury; PAL: Physical Activity Level; SCI: spinal cord injury; TSI: Time since
474 injury.

Table 2: Test-retest reliability statistics for peak physiological variables obtained in RAMP and PRET_{max} protocols.

	RAMP				PRET _{max}			
	CV (%)	ME	SDD	ICC _{3,1}	CV (%)	ME	SDD	ICC _{3,1}
$\dot{V}O_{2peak}$ (L·min ⁻¹)	4.6	0.12	0.16	0.95	5.4	0.13	0.18	0.93
$\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	5.9	1.70	2.36	0.96	8.1	2.20	3.04	0.92
HR _{peak} (beats·min ⁻¹)	3.8	11	15	0.95	3.7	8	12	0.97
PO _{peak} (W)	3.6	5	7	0.99	8.8	13	18	0.94
RER _{peak}	3.8	0.09	0.13	0.90	2.7	0.06	0.08	0.92

ME and SDD values are presented in the given unit of measurement for each variable. CV: Coefficient of Variation; HR_{peak}: peak heart rate; ICC: Intraclass correlation coefficient; ME: measurement error; PO_{peak}: peak power output; PRET_{max}: maximal perceptually-regulated exercise test; RAMP: ramp-incremented max test; RER_{peak}: peak respiratory exchange ratio; SDD: smallest detectable difference; $\dot{V}O_{2peak}$: peak oxygen uptake.

Table 3: Peak physiological and perceptual responses to RAMP and PRET_{max}.

	RAMP	PRET _{max}	Mean difference (95% CI)	<i>P</i>
$\dot{V}O_{2peak}$ (L·min ⁻¹)	1.3 ± 0.3	1.2 ± 0.3	0.1 (-0.0 - 0.2)	0.06
$\dot{V}O_{2peak}$ (ml·kg ⁻¹ ·min ⁻¹)	14.8 ± 5.5	13.9 ± 5.2	0.9 (-0.1 - 1.8)	0.08
RER _{peak}	1.25 ± 0.20	1.22 ± 0.14	0.04 (-0.05 - 0.13)	0.37
HR _{peak} (beats·min ⁻¹)	141 ± 29	134 ± 29	7 (-3 - 18)	0.15
PO _{peak} (W)	81 ± 28	76 ± 34	6 (-3 - 14)	0.16
Duration (s)	674 ± 191	600 ± 0	74 (-63 - 210)	0.25
RPE _P	20 (19 - 20)*	19 (19 - 20)		0.03
RPE _C	20 (18 - 20)	19 (18 - 20)		>0.95
RPE _O	20 (18 - 20)	19 (19 - 20)		0.46
FS _{peak}	-3 (-4 - -1)*	0 (-2 - 1)		0.02
FS _{average}	2 (1 - 2)	2 (2 - 3)		0.21

Ratio data are presented as mean ± SD whilst ordinal data are presented as median (inter-quartile range). * = significantly different to PRET_{max}, *P* < 0.05. CI: confidence interval; FS_{peak}: peak Feeling Scale rating; FS_{average}: average Feeling Scale rating; HR_{peak}: peak heart rate; PO_{peak}: peak power output; PRET_{max}: maximal perceptually-regulated exercise test; RAMP: ramp-incremented exercise test; RER: peak respiratory exchange ratio; RPE_C: central Rating of Perceived Exertion; RPE_O: overall Rating of Perceived Exertion; RPE_P: peripheral Rating of Perceived Exertion; $\dot{V}O_{2peak}$: peak oxygen uptake.

Table 4: Group-averaged correlations for differentiated RPE with objective markers of exercise intensity from the 2nd trial of each protocol

	RAMP	PRET _{max}
RPE _P : $\dot{V}O_2$	0.949 (0.769 - 0.990)	0.957 (0.640 - 0.996)
RPE _P :HR	0.967 (0.806 - 0.995)	0.971 (0.840 - 0.995)
RPE _P :PO	0.990 (0.947 - 0.998)*	0.970 (0.786 - 0.996)
RPE _C : $\dot{V}O_2$	0.956 (0.779 - 0.992)	0.954 (0.610 - 0.996)
RPE _C :HR	0.973 (0.788 - 0.997)	0.960 (0.641 - 0.996)
RPE _C :PO	0.991 (0.946 - 0.999)*	0.964 (0.610 - 0.997)
RPE _O : $\dot{V}O_2$	0.959 (0.676 - 0.996)	0.947 (0.458 - 0.996)
RPE _O :HR	0.969 (0.810 - 0.995)	0.959 (0.612 - 0.996)
RPE _O :PO	0.988 (0.932 - 0.998)*	0.965 (0.662 - 0.997)

Data are presented as mean (95% Confidence Interval). * = significant main effect of protocol for RPE:PO relationships, RAMP greater than PRET_{max}, $P < 0.05$. HR: heart rate; PO: power output; PRET_{max}: maximal perceptually-regulated exercise test; RAMP: ramp-incremented exercise test; RPE_C: central Rating of Perceived Exertion; RPE_O: overall Rating of Perceived Exertion; RPE_P: peripheral Rating of Perceived Exertion; $\dot{V}O_2$: oxygen uptake.

Table 5: Feeling Scale rating at submaximal RPE during RAMP and PRET_{max}

	RAMP	PRET _{max}
RPE 11	3.0 (2.9 - 4.0)	4.0 (3.5 - 4.5)
RPE 13	2.3 (1.0 - 3.0)	3.3 (2.9 - 3.6)*
RPE 15	0.8 (0.4 - 1.6)	2.0 (1.0 - 3.0)*
RPE 17	0.0 (-1.2 - 1.1)	1.5 (0.9 - 2.1)*

Data are presented as median (interquartile range). *: significantly greater than during RAMP, $P < 0.05$. PRET_{max} = maximal perceptually-regulated exercise test; RAMP = ramp-incremented exercise test; RPE = Rating of Perceived Exertion.