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Perceived exertion responses to wheelchair propulsion differ between novice able-bodied and trained wheelchair sportspeople

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Abstract

Objectives: To investigate peripheral (RPE_P) and central (RPE_C) rating of perceived exertion during wheelchair propulsion in untrained able-bodied (AB) participants, and trained wheelchair rugby athletes with and without cervical spinal cord injury (CSCI).

Design: Cross-sectional study.

Methods: 38 participants (AB: $n = 20$; wheelchair rugby athletes with CSCI: $n = 9$; without CSCI: $n = 9$) completed an incremental wheelchair propulsion test to exhaustion on a motorised treadmill. Gas exchange measures and heart rate (HR) were collected throughout. RPE_P and RPE_C on the Category Ratio-10 were verbally recorded each minute. Blood lactate concentration ($[BLa]$) was determined post-test.

Results: Between 50-100% peak oxygen uptake ($\dot{V}O_{2peak}$), RPE_P was greater than RPE_C in AB ($p < 0.05$), but not in athletes with ($p = 0.07$) or without ($p = 0.16$) CSCI. RPE_P was greater in AB compared to players with CSCI (Effect sizes: 1.24-1.62), as were respiratory exchange ratio (1.02 ± 0.10 vs. 0.82 ± 0.11 , $p < 0.05$) and $[BLa]_{peak}$ (7.98 ± 2.53 vs 4.66 ± 1.57 mmol·L⁻¹). RPE_C was greater in athletes without CSCI compared to those with CSCI (Effect sizes: 0.70-1.38), as were HR (166 ± 20 vs. 104 ± 15 beats·min⁻¹, $p < 0.05$) and ventilation (59.2 ± 28.8 vs. 35.1 ± 16.6 L·min⁻¹, $p = 0.01$).

Conclusion: RPE_P was dominant over RPE_C during wheelchair propulsion for untrained AB participants. For athletes with CSCI, lower RPE_P and RPE_C were reported at the same % $\dot{V}O_{2peak}$ compared to those without CSCI. The mechanism for this remains to be fully elucidated.

Key Words: differentiated, perceived exertion, tetraplegia, afferent feedback, central drive

Introduction

The purpose of population-specific exercise guidelines is to describe the duration, frequency, and intensity of exercise necessary for improving fitness and health.¹ For adults with a spinal cord injury (SCI) the exercise guidelines recommend engaging in at least 20 min aerobic exercise, twice weekly, at a moderate to vigorous intensity.^{2,3} That said, though objective markers such as oxygen uptake ($\dot{V}O_2$) and heart rate (HR) are preferred for prescribing exercise intensity,⁴ the ease of application of Ratings of Perceived Exertion (RPE) offers an enticing alternative. However, a recent systematic review concluded that there is insufficient evidence regarding the reliable and valid use of RPE to regulate exercise intensity in adults with SCI, due to a lack of consistent results from high quality studies.⁵ As such, more evidence is required to understand RPE responses in persons with SCI in order to inform its use for exercise prescription.

Van der Scheer et al.⁵ highlighted how greater understanding is needed over the use of differentiated RPE in adults with SCI, as opposed to a whole-body, overall rating of RPE (RPE_O). When differentiating RPE, participants can report a peripheral RPE (RPE_P), based on the exertion of the active muscles, and central RPE (RPE_C) based on cardiorespiratory cues.⁶ For upper body exercise (the modality commonly used by persons with SCI), where the musculature is typically smaller, it may be that exertional cues from the periphery are different to those from the cardiorespiratory system.^{7,8} Trained wheelchair rugby players with cervical SCI (CSCI) show no difference in the relationships between RPE_O , RPE_P , or RPE_C , and $\dot{V}O_2$, or the differentiated RPE at peak oxygen uptake ($\dot{V}O_{2peak}$).⁹ Conversely, a recent study showed that RPE_P increases significantly faster than RPE_C during incremental arm crank ergometry in untrained people with CSCI.⁸ These divergent findings in CSCI suggest a potential role of training status in the differentiated RPE response to upper body exercise. Understanding the RPE_P and RPE_C responses to exercise in untrained AB and trained people with, and without, CSCI will aid the implementation of exercise training programmes with differentiated RPE in these populations.

Athletes eligible for classification in wheelchair rugby include those with CSCI, and other forms of disability. These players without CSCI, like AB, have unimpaired afferent feedback from the upper body to the brain. However, for players with a complete CSCI the number of afferent signals informing the brain via neural pathways will be inversely related to lesion level. Group III and IV afferents with receptors located within skeletal muscle respond to mechanical and chemical stimuli induced by muscle contraction and contribute to the autonomic control of cardiovascular and ventilatory responses to exercise,¹⁰ and have been implicated in the generation of RPE.¹¹ Sympathetic innervation of the heart, intercostal and abdominal muscles arise from the thoracic region of the spinal cord,¹² leading to blunted peak HR (HR_{peak})¹³ and limiting inspiratory and expiratory efforts during exercise^{12,14,15} in complete CSCI. It is hence possible that injury-dependent consequences also impact the RPE reported by people with CSCI during exercise. Comparing the physiological and differentiated RPE responses to exercise between AB and wheelchair rugby players with and without CSCI may help elucidate the mechanisms involved in generating RPE.

As such, the primary aim of this study was to investigate the effect of training status on the differentiated RPE response to incremental exercise by comparing responses in AB and trained athletes with CSCI. It was hypothesised that RPE_P would increase significantly faster than RPE_C with increasing exercise intensity in AB, but not trained wheelchair rugby athletes. A secondary aim was to investigate the role of CSCI on RPE responses.

Methods

Thirty-eight healthy adults who provided written, informed consent, volunteered to take part in the study, which was approved by the Loughborough University Ethics Human Participants Subcommittee (R17-P130). The sample comprised three subgroups: AB ($n = 20$; 22 ± 2 years; 86.7 ± 14.4 kg); and experienced wheelchair rugby players with complete CSCI (CSCI; $n = 9$; 29 ± 7 years; 68.9 ± 12.4 kg), or a disability other than CSCI (Non-SCI; $n = 9$; 28 ± 5 years; 60.1 ± 12.8 kg). All participants were male except for one female participant with CSCI. AB participants were untrained in upper body aerobic exercise but were habitually trained and competing at a university sport level. The Non-SCI

group included participants with amputation ($n = 4$), arthrogryposis, cerebral palsy, osteogenesis imperfecta, polyneuropathy, and Roberts syndrome (all $n = 1$), thus having no paralysis of the upper body and trunk.

Participants completed a single trial consisting of submaximal and maximal wheelchair propulsion tests on a motorised treadmill (HP Cosmos, Traunstein, Germany). AB participants completed two prior trials to familiarise them with WCP. Familiarisation was not needed for the athletes given their training status and that all were manual wheelchair users. Familiarisation and main trials were separated by a minimum of 2, and maximum of 5 days.

The first familiarisation trial consisted of a 10 min period at $1.0\text{--}1.2\text{ m}\cdot\text{s}^{-1}$ with participants free to experiment and find a propulsion technique they were comfortable with. No training was given, however participants were encouraged to vary their push frequency and contact angle with the push rim until finding a preferable combination.¹⁶ Following this, AB performed two, 3 min blocks at 1.4 and $1.6\text{ m}\cdot\text{s}^{-1}$. The second familiarisation trial exposed participants to maximal intensity wheelchair propulsion and utilised the same protocol as the main trial, including all measures.

Following a self-selected warm up, participants completed a submaximal test comprising six to eight, discontinuous, 3 min stages. Starting speed was between 1.0 and $2.2\text{ m}\cdot\text{s}^{-1}$, depending on experience and level of physical function, and was increased by $0.2\text{ m}\cdot\text{s}^{-1}$ in AB and CSCI, and by $0.3\text{ m}\cdot\text{s}^{-1}$ in Non-SCI. Oxygen uptake ($\dot{V}O_2$), minute ventilation ($\dot{V}E$) and respiratory exchange ratio (RER) via online gas analysis (Metalyzer 3B, Cortex, Leipzig, Germany) and HR (RS400, Polar, Kempele, Finland) were collected throughout. At the end of each stage treadmill speed was reduced to allow a capillary blood sample to be taken from the earlobe for measurement of blood lactate concentration ([BLa]) using Biosen C-line monitor (EKF diagnostics, Barleben, Germany). Once the sample had been obtained (30–45 s) the next stage commenced. The test was terminated once [BLa] exceeded $4\text{ mmol}\cdot\text{L}^{-1}$.

Participants then received 15 min of active recovery and/or rest before performing a graded exercise test ($1.2\text{--}3.2\text{ m}\cdot\text{s}^{-1} + 0.1\text{ m}\cdot\text{s}^{-1}\cdot\text{min}^{-1}$) to volitional exhaustion. Starting speed was set to the speed

from the submaximal test where [BLa] increased ($\sim 0.5 \text{ mmol} \cdot \text{L}^{-1}$) above the resting value. Gas exchange variables and HR were collected throughout, with [BLa] determined immediately post-test. RPE_P and RPE_C were verbally reported at the end of each minute throughout, as well as at termination of the test on the CR-10 scale.¹⁷ Participants were instructed to focus on how hard and strenuous the task felt in the working musculature (RPE_P) and cardiorespiratory systems (RPE_C), and not on any sensations of pain or discomfort.^{6,18}

Statistical analyses were performed using IBM SPSS Statistics 23 (SPSS Inc., Chicago, IL.). Data are presented as mean $\pm$ SD, with statistical significance accepted at $p < 0.05$. Data were checked for normal distribution using the Shapiro Wilk statistic. Differences in peak responses between AB, Non-SCI and CSCI were assessed by one-way analysis of variance (ANOVA) with Bonferroni post-hoc for multiple comparisons. The Greenhouse-Geisser epsilon was used unless it was greater than 0.75, in which case the Huynh-Feldt epsilon was used.

RPE_P and RPE_C were fit using a quadratic function against normalised test duration and exercise intensity ($\% \dot{V}\text{O}_{2\text{peak}}$).⁸ The RPE_P and RPE_C corresponding to 10% intervals for the entire test duration and from 50 to 100% $\dot{V}\text{O}_{2\text{peak}}$ were then calculated. Three-way repeated measures ANOVA were used to assess the effect of RPE differential, group, and time or $\% \dot{V}\text{O}_{2\text{peak}}$. In the event of a significant interaction effect involving the group factor, separate two-way repeated measures ANOVA, with Bonferroni post-hoc, were used to assess differences in RPE_P and RPE_C within subgroups. For the RPE values modelled against time these were 2 (RPE_P , RPE_C) $\times$ 10 (10-100% test duration) ANOVA, and for the values modelled against $\dot{V}\text{O}_{2\text{peak}}$ were 2 (RPE_P , RPE_C) $\times$ 6 (50-100% $\dot{V}\text{O}_{2\text{peak}}$) ANOVA. In each case the Cohen's effect sizes (ES) and 90% confidence interval¹⁹ were calculated for RPE_P and RPE_C between subgroups from 50-100% $\dot{V}\text{O}_{2\text{peak}}$ and categorised as trivial (< 0.2), small (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0) and very large (> 2.0).²⁰

RER , $\dot{V}\text{E}$ and HR were fit against $\% \dot{V}\text{O}_{2\text{peak}}$ using a linear function, with values extracted corresponding to 10% intervals from 50-100% $\dot{V}\text{O}_{2\text{peak}}$. Differences between subgroups were assessed

using 2 x 6 mixed model ANOVA with the between measure being “group” and the within measure being “ $\dot{V}O_{2peak}$ ”.

Results

Maximal responses to incremental wheelchair propulsion are presented in Table 1. Absolute $\dot{V}O_{2peak}$ was greater in AB compared to Non-SCI (mean difference, 95% confidence interval: 0.6, 0.1-1.2 L·min⁻¹, $p = 0.03$) and CSCI (1.6, 1.0-2.2 L·min⁻¹, $p < 0.005$), as well as Non-SCI compared to CSCI (1.0, 0.3-1.6 L·min⁻¹, $p = 0.01$). Relative $\dot{V}O_{2peak}$ was greater in AB (14.3, 8.5-20.2 ml·kg⁻¹·min⁻¹, $p < 0.005$) and Non-SCI (18.8, 1.9-25.7 ml·kg⁻¹·min⁻¹, $p < 0.005$) than CSCI. HR_{peak} was greater in AB compared to CSCI (56, 40-72 beats·min⁻¹, $p < 0.005$), but also Non-SCI compared to AB (16, 2-30 beats·min⁻¹, $p = 0.03$) and CSCI (72, 54-90 beats·min⁻¹, $p < 0.005$). Peak [BLa] was significantly greater in AB (3.31, 1.04-5.60 mmol·L⁻¹, $p < 0.005$) and Non-SCI (4.03, 1.40-6.66 mmol·L⁻¹, $p < 0.005$) than in CSCI (4.66 ± 1.57 mmol·L⁻¹). Peak propulsion speed was significantly greater in Non-SCI than AB (0.8, 0.4-1.2 m·s⁻¹, $p < 0.005$) and CSCI (1.1, 0.6-1.6 m·s⁻¹, $p < 0.005$).

There was a significant interaction between differentiated RPE, normalised test duration and group ($p < 0.005$). In AB there was a significant main effect of RPE differential ($F_{(1.00)} = 55.14$, $p < 0.005$) and RPE-time interaction ($F_{(1.83)} = 27.99$, $p < 0.005$). Bonferroni post-hoc tests showed RPE_P was significantly greater than RPE_C (5.1 ± 3.0 vs 3.4 ± 2.5), with RPE_P developed quicker than RPE_C (Figure 1a). In Non-SCI and CSCI there was no main effect of RPE differential ($F_{(1.00)} < 4.81$, $p > 0.06$) or RPE-time interaction ($F_{(< 1.49)} < 2.24$, $p > 0.16$, Figure 1b,c).

There was also a significant interaction between differentiated RPE, % $\dot{V}O_{2peak}$ and group ($p < 0.005$). In AB there was a significant main effect of RPE differential ($F_{(1.00)} = 59.40$, $p < 0.005$) and RPE-% $\dot{V}O_{2peak}$ interaction ($F_{(1.28)} = 12.63$, $p = 0.01$). Bonferroni post-hoc showed RPE_P was significantly greater than RPE_C (6.6 ± 2.8 vs 4.5 ± 2.5), whilst RPE_P developed significantly faster than RPE_C (Figure 1d). In Non-SCI and CSCI there was no effect of RPE differential ($F_{(1.00)} < 4.25$, $p > 0.07$) or RPE-% $\dot{V}O_{2peak}$ interaction ($F_{(< 1.50)} < 4.03$, $p > 0.06$, Figure 1e,f). The ES comparing the difference in RPE_P and RPE_C between subgroups at 50-100% $\dot{V}O_{2peak}$ are presented in Figure 2. The RPE_P in AB was

greater than CSCI with a large ES, whilst RPE_C was greater in Non-SCI compared to CSCI with a moderate to large ES.

The RER was significantly greater in AB than CSCI from 50-100% $\dot{V}O_{2peak}$ (1.02 ± 0.10 vs 0.82 ± 0.11 ; $0.20, 0.15-0.25$; $F_{(1.00)} = 56.42$, $p < 0.005$; $ES = 1.87$), though there was no difference in propulsion speed ($F_{(1.00)} = 3.68$, $p = 0.07$). The HR was greater in Non-SCI (166 ± 20 beats $\cdot$ min $^{-1}$) compared to AB (146 ± 24 beats $\cdot$ min $^{-1}$; $20, 9-30$ beats $\cdot$ min $^{-1}$; $F_{(1.00)} = 14.27$, $p = 0.01$; $ES = 0.88$) and CSCI (104 ± 15 beats $\cdot$ min $^{-1}$; $62, 52-72$ beats $\cdot$ min $^{-1}$; $F_{(1.00)} = 181.27$, $p < 0.005$; $ES = 3.48$) from 50-100% $\dot{V}O_{2peak}$. Propulsion speed was also significantly greater in Non-SCI than AB (3.1 ± 0.6 vs 2.3 ± 0.5 m $\cdot$ s $^{-1}$; $0.8, 0.4-1.1$ m $\cdot$ s $^{-1}$; $F_{(1.00)} = 21.84$, $p < 0.005$; $ES = 1.50$). In contrast, $\dot{V}E$ was significantly greater in AB than in Non-SCI (75.0 ± 26.0 vs 59.2 ± 28.8 L $\cdot$ min $^{-1}$; $15.8, 3.7-27.9$ L $\cdot$ min $^{-1}$; $F_{(1.00)} = 7.17$, $p = 0.01$; $ES = 0.59$), though was also greater in Non-SCI than CSCI (59.2 ± 28.8 vs 35.1 ± 16.6 L $\cdot$ min $^{-1}$; $24.1, 7.8-40.5$ L $\cdot$ min $^{-1}$; $F_{(1.00)} = 9.77$, $p = 0.01$; $ES = 1.03$).

Discussion

This study examined the use of differentiated RPE to provide a thorough insight into the perceptual responses of untrained AB and trained wheelchair rugby athletes with and without CSCI. The principal finding was that in untrained AB performing incremental wheelchair propulsion, RPE_P was significantly greater than RPE_C between 50 and 100% $\dot{V}O_{2peak}$. This contrasts with trained wheelchair rugby players who exhibited no difference between RPE_P and RPE_C between 50 and 100% $\dot{V}O_{2peak}$, irrespective of their disability.

These findings corroborate previous research that has found a perceptual signal dominance of RPE_P over RPE_C in untrained AB persons performing arm crank,²¹ handcyc²² and wheelchair propulsion^{7,23,24} exercise. Similar investigations into the differentiated RPE of CSCI have proven equivocal. In contrast to the present findings, recreationally-active people with CSCI showed accelerated RPE_P compared to RPE_C during incremental arm crank ergometry.⁸ This would suggest a role of training status on the differentiated RPE response to exercise in CSCI. Also of note is that wheelchair rugby players without CSCI showed no difference between RPE_P and RPE_C , whereas

untrained AB did. When running, no difference in the RPE_P or RPE_C were found between recreationally-active, or trained participants at equal % $\dot{V}O_{2peak}$.²⁵ Furthermore, running training leading to improvements in $\dot{V}O_{2peak}$ had no impact on the RPE at equal % $\dot{V}O_{2peak}$.²⁶ Together these findings suggest that the relationship between differentiated RPE and % $\dot{V}O_{2peak}$ differs between lower and upper body exercise, and that it may be more susceptible to change during upper body exercise. It is possible that the change in relationship in RPE is related to an increase in efficiency with prolonged training.²⁷ This has important implications for professionals working with individuals with CSCI to design and implement an exercise training programme. For example, when an individual is untrained the differentiated RPE may be a better indicator of exercise intensity, however with training and the diminishing difference between differentiated RPE, the RPE_O may be suitable.

This is the first study to note that AB, and wheelchair rugby players with and without CSCI exhibit different RPE_P and RPE_C at the same % $\dot{V}O_{2peak}$ during wheelchair propulsion. Specifically, RPE_P was greater in AB, and RPE_C greater in athletes without CSCI, compared to those with CSCI. The physiological consequences of CSCI make it an interesting experimental model by which to investigate factors involved in generating RPE, particularly with a complete CSCI in which no motor or sensory function is preserved below the level of the injury. A principle contention surrounds whether the generation of RPE is independent, or not, of afferent feedback from the working musculature.¹⁸ Whilst there is evidence to suggest a role of Group III and IV muscle afferents in generating RPE,¹¹ another perspective is that RPE is independent of afferent feedback and instead reflects corollary discharges emanating from pre and/or motor areas of the brain that are simultaneously directed to sensory areas involved in perception..²⁸ According to this view, an increase in RPE reflects an increase in motor related cortical potential, an index of central motor command. This is supported by experimental evidence showing increases in both RPE and cortical potentials when fatigued muscles are exercised,²⁹ and decreases by the administration of caffeine causing a decrease in the activity of premotor and motor areas of the brain.³⁰ The present finding of increased RPE_C in athletes without, compared to those with, CSCI could support the role of central motor command in generating RPE. Paralysis caused by CSCI leads to impaired sympathetic innervation of cardiac muscle, as well as of intercostal and abdominal

muscles involved in inspiratory and expiratory efforts.¹² Along with increased RPE_C, athletes without CSCI had greater HR and $\dot{V}E$ responses than those with CSCI. This could reflect greater central motor command, due to the increased active musculature, thereby leading to the increased RPE_C. However, the increased active musculature could also be generating greater feedback via Group III and IV muscle afferents and be contributing to the increased RPE_C. As such, further investigations are required to independently assess the role of central motor command in generating RPE.

An alternative hypothesis concerns whether afferent feedback contributes to the generation of RPE. Whereas central motor command appears to exert its effect on RPE independently,²⁹ evidence also implicates Group III and IV afferents in the generation of RPE.¹¹ In the present study, RPE_P was increased in AB compared to wheelchair rugby players with CSCI from 50-100% $\dot{V}O_{2peak}$ with large ES, despite no difference in the propulsion speed. However, not only was RER significantly greater in AB compared to those with CSCI at the same % $\dot{V}O_{2peak}$, post-test [BLa] was also greater in AB. This apparent increased rate of glycolysis in AB likely led to a greater accumulation of metabolites, and thereby increased afferent feedback and potentially contributing to the higher RPE_P in AB. These results would hence serve to support the hypothesis that afferent feedback does indeed contribute to generating RPE.

Conclusions

In conclusion, during incremental wheelchair propulsion RPE_P was significantly greater than RPE_C in untrained AB, whilst no differences between RPE_P and RPE_C were found in trained wheelchair rugby players, irrespective of disability. The noted increases in RPE_P for AB compared to athletes with CSCI supports a role of afferent feedback in generating RPE.

Practical applications

- For individuals untrained in upper body exercise, differentiated RPE should be collected to gain a more complete representation of the exertion felt.
- As an individual becomes more trained and the differentiated RPE become more similar, then a single overall RPE may be appropriate.

- For a practitioner working with an athlete group containing different disabilities, the same RPE prescription will not equate to the same relative intensity for each athlete because of disability-related consequences on the mechanism of the RPE response.

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237 **References**

- 238 1 American College of Sports Medicine, Riebe D, Ehrman JK, et al. *ACSM's guidelines for*
239 *exercise testing and prescription*. Tenth edit. Philadelphia, PA, Wolters Kluwer, 2018.

- 240 2 Martin Ginis KA, van der Scheer JW, Latimer-Cheung AE, et al. Evidence-based scientific
241 exercise guidelines for adults with spinal cord injury: an update and a new guideline. *Spinal*
242 *Cord* 2018; 56(4):308–321. Doi: 10.1038/s41393-017-0017-3.

- 243 3 van der Scheer JW, Martin Ginis KA, Ditor DS, et al. Effects of exercise on fitness and health
244 of adults with spinal cord injury. *Neurology* 2017; 89(7):736–745. Doi:
245 10.1212/WNL.0000000000004224.

- 246 4 Garber CE, Blissmer B, Deschenes MR, et al. American College of Sports Medicine Position
247 stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory,
248 musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing
249 exercise. *Med Sci Sports Exerc* 2011; 43(7):1334–1359. Doi: 10.1249/MSS.0b013e318213febf.

- 250 5 van der Scheer JW, Hutchinson M, Paulson T, et al. Reliability and validity of subjective
251 measures of aerobic intensity in adults with spinal cord injury: a systematic review. *PM&R*
252 2018; 10(2):194–207. Doi: 10.1016/j.pmrj.2017.08.440.

- 253 6 Marcora SM. Effort: Perception of. In: Goldstein E. B., editor. *Encycl. Percept.* 1st ed.
254 Thousand Oaks, California, Sage, 2010. p. 380–383.

- 255 7 Lenton JP, Fowler NE, van der Woude L, et al. Wheelchair propulsion: effects of experience
256 and push strategy on efficiency and perceived exertion. *Appl Physiol Nutr Metab* 2008;
257 33(5):870–879. Doi: 10.1139/H08-072.

- 258 8 Au JS, Totosy de Zepetnek JO, MacDonald MJ. Modeling perceived exertion during graded arm
259 cycling exercise in spinal cord injury. *Med Sci Sports Exerc* 2017; 49(6):1190–1196. Doi:
260 10.1249/MSS.0000000000001203.

- 261 9 Paulson TA, Bishop NC, Leicht CA, et al. Perceived exertion as a tool to self-regulate exercise
262 in individuals with tetraplegia. *Eur J Appl Physiol* 2013; 113(1):201–209. Doi:
263 10.1007/s00421-012-2426-5.
- 264 10 Amann M, Sidhu SK, Weavil JC, et al. Autonomic responses to exercise: group III/IV muscle
265 afferents and fatigue. *Auton Neurosci* 2015; 188:19–23. Doi: 10.1016/j.autneu.2014.10.018.
- 266 11 Amann M, Blain GM, Proctor LT, et al. Group III and IV muscle afferents contribute to
267 ventilatory and cardiovascular response to rhythmic exercise in humans. *J Appl Physiol* 2010;
268 109(4):966–976. Doi: 10.1152/JAPPLPHYSIOL.00462.2010.
- 269 12 Krassioukov A. Autonomic function following cervical spinal cord injury. *Respir Physiol*
270 *Neurobiol* 2009; 169(2):157–164. Doi: 10.1016/j.resp.2009.08.003.
- 271 13 Leicht CA, Bishop NC, Goosey-Tolfrey VL. Submaximal exercise responses in tetraplegic,
272 paraplegic and non spinal cord injured elite wheelchair athletes. *Scand J Med Sci Sports* 2012;
273 22(6):729–736. Doi: 10.1111/j.1600-0838.2011.01328.x.
- 274 14 West CR, Campbell IG, Goosey-Tolfrey VL, et al. Effects of abdominal binding on field-based
275 exercise responses in Paralympic athletes with cervical spinal cord injury. *J Sci Med Sport*
276 2014; 17(4):351–355. Doi: 10.1016/J.JSAMS.2013.06.001.
- 277 15 West CR, Goosey-Tolfrey VL, Campbell IG, et al. Effect of abdominal binding on respiratory
278 mechanics during exercise in athletes with cervical spinal cord injury. *J Appl Physiol* 2014;
279 117(1):36–45. Doi: 10.1152/japplphysiol.00218.2014.
- 280 16 Vegter RJK, Hartog J, de Groot S, et al. Early motor learning changes in upper-limb dynamics
281 and shoulder complex loading during handrim wheelchair propulsion. *J Neuroeng Rehabil*
282 2015; 12(1):26. Doi: 10.1186/s12984-015-0017-5.
- 283 17 Borg GA. *Borg's Perceived Exertion and Pain Scales*. Champaign, IL, Human Kinetics, 1998.
- 284 18 Pageaux B. Perception of effort in exercise science: definition, measurement and perspectives.

285 *Eur J Sport Sci* 2016; 16(8):885–894. Doi: 10.1080/17461391.2016.1188992.

286 19 Cohen J. A power primer. *Psychol Bull* 1992; 112(1):155–159. Doi: 10.1037/0033-
287 2909.112.1.155.

288 20 Batterham AM, Hopkins WG. Making meaningful inferences about magnitudes. *Int J Sports*
289 *Physiol Perform* 2006; 1(1):50–57.

290 21 Pandolf KB, Billings DS, Drolet LL, et al. Differential ratings of perceived exertion and
291 various physiological responses during prolonged upper and lower body exercise. *Eur J Appl*
292 *Physiol Occup Physiol* 1984; 53(1):5–11.

293 22 Hutchinson MJ, Paulson TAW, Eston R, et al. Assessment of peak oxygen uptake during
294 handcycling: Test-retest reliability and comparison of a ramp-incremented and perceptually-
295 regulated exercise test. *PLoS One* 2017; 12(7):e0181008. Doi: 10.1371/journal.pone.0181008.

296 23 Goosey-Tolfrey VL, Kirk JH. Effect of push frequency and strategy variations on economy and
297 perceived exertion during wheelchair propulsion. *Eur J Appl Physiol* 2003; 90(1–2):154–158.
298 Doi: 10.1007/s00421-003-0875-6.

299 24 Paulson TA, Bishop NC, Eston RG, et al. Differentiated perceived exertion and self-regulated
300 wheelchair exercise. *Arch Phys Med Rehabil* 2013; 94(11):2269–2276. Doi:
301 10.1016/j.apmr.2013.03.018.

302 25 Bolgar MR, Baker CE, Goss FL, et al. Effect of exercise intensity on differentiated and
303 undifferentiated ratings of perceived exertion during cycle and treadmill exercise in
304 recreationally active and trained women. *J Sports Sci Med* 2010; 9(4):557–563.

305 26 Ekblom B, Goldbarg AN. The influence of physical training and other factors on the subjective
306 rating of perceived exertion. *Acta Physiol Scand* 1971; 83(3):399–406. Doi: 10.1111/j.1748-
307 1716.1971.tb05093.x.

308 27 Montero D, Lundby C. The effect of exercise training on the energetic cost of cycling. *Sport*

309 *Med* 2015; 45(11):1603–1618. Doi: 10.1007/s40279-015-0380-1.

310 28 Marcora S. Perception of effort during exercise is independent of afferent feedback from
311 skeletal muscles, heart, and lungs. *J Appl Physiol* 2009; 106(6):2060–2062. Doi:
312 10.1152/jappphysiol.90378.2008.

313 29 de Morree HM, Klein C, Marcora SM. Perception of effort reflects central motor command
314 during movement execution. *Psychophysiology* 2012; 49(9):1242–1253. Doi: 10.1111/j.1469-
315 8986.2012.01399.x.

316 30 de Morree HM, Klein C, Marcora SM. Cortical substrates of the effects of caffeine and time-
317 on-task on perception of effort. *J Appl Physiol* 2014; 117(12):1514–1523. Doi:
318 10.1152/jappphysiol.00898.2013.

319

320 Table 1: Peak responses to maximal incremental wheelchair propulsion.

	AB	Non-SCI	CSCI
$\dot{V}O_{2\text{peak}}$ ($\text{L} \cdot \text{min}^{-1}$)	$3.1 \pm 0.5^{*\dagger}$	$2.4 \pm 0.7^{\dagger}$	1.5 ± 0.5
$\dot{V}O_{2\text{peak}}$ ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	$35.7 \pm 6.0^{\dagger}$	$40.1 \pm 5.3^{\dagger}$	21.3 ± 5.9
HR_{peak} ($\text{beats} \cdot \text{min}^{-1}$)	$172 \pm 18^{\dagger}$	$188 \pm 3^{\dagger\ddagger}$	117 ± 11
RER_{peak}	$1.16 \pm 0.10^{\dagger}$	1.13 ± 0.08	1.01 ± 0.06
$\dot{V}E_{\text{peak}}$ ($\text{L} \cdot \text{min}^{-1}$)	$113.0 \pm 18.9^{\dagger}$	$96.3 \pm 34.3^{\dagger}$	53.2 ± 17.9
$[\text{BLa}]_{\text{peak}}$ ($\text{mmol} \cdot \text{L}^{-1}$)	$7.98 \pm 2.53^{\dagger}$	$8.69 \pm 2.02^{\dagger}$	4.66 ± 1.57
Peak speed ($\text{m} \cdot \text{s}^{-1}$)	2.7 ± 0.4	$3.5 \pm 0.5^{\dagger\ddagger}$	2.4 ± 0.5
Time to exhaustion (s)	$684 \pm 112^{\dagger}$	$633 \pm 120^{\dagger}$	475 ± 109

321 *: significantly greater than Non-SCI, $\dagger$: significantly greater than CSCI, $\ddagger$: significantly greater than
322 AB.

323 **Figure captions**

324 Figure 1: Development of RPE_P (solid lines) and RPE_C (dashed lines) using the CR-10, relative to
325 normalised test duration (a-c) and $\dot{V}O_{2peak}$ (d-f) in AB (a, d), Non-SCI (b, e) and CSCI (c, f) groups. *:
326 RPE_P greater than RPE_C, $P < 0.05$.

327 Figure 2: Effect sizes for the difference in both RPE_P and RPE_C from 50 to 100% $\dot{V}O_{2peak}$ between AB,
328 Non-SCI and CSCI. Points to the right of the “Trivial” section identify instances where AB > Non-
329 SCI, AB > CSCI, and Non-SCI > CSCI. Points to the left of the “Trivial” section identify where AB <
330 Non-SCI, AB < CSCI, and Non-SCI < CSCI. Effect sizes were categorised as trivial (< 0.2), small
331 (0.2-0.6), moderate (0.6-1.2), large (1.2-2.0) and very large (> 2.0).