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9 **Sex differences in wheelchair propulsion biomechanics and mechanical efficiency**
10 **in novice young able-bodied adults**

11

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14

15 **Abstract**

16 An awareness of sex differences in gait can be beneficial for detecting the early stages
17 of gait abnormalities that may lead to pathology. The same may be true for wheelchair
18 propulsion. The aim of this study was to determine the effect of sex on wheelchair
19 biomechanics and mechanical efficiency in novice young able-bodied wheelchair
20 propulsion. Thirty men and thirty women received 12-minutes of familiarization
21 training. Subsequently, they performed two 10-metre propulsion tests to evaluate
22 comfortable speed (CS). Additionally, they performed a 4-min submaximal propulsion
23 test on a treadmill at CS, 125% and 145% of CS. Propulsion kinetics (via Smart^{wheel})
24 and oxygen uptake were continuously measured in all tests and were used to determine

25 gross mechanical efficiency (GE), net efficiency (NE) and fraction of effective force
26 (FEF). Ratings of perceived exertion (RPE) were assessed directly after each trial.
27 Results indicated that CS for men was faster (0.98 ± 0.24 m/s) compared to women
28 (0.71 ± 0.18 m/s). A lower GE was found in women compared to men. Push percentage,
29 push angle and local RPE were different across the three speeds and between men and
30 women. NE and FEF were not different between groups. Thus, even though their CS
31 was lower, women demonstrated a higher locally perceived exertion than men. The
32 results suggest sex differences in propulsion characteristics and GE. These insights may
33 aid in optimizing wheelchair propulsion through proper training and advice to prevent
34 injuries and improve performance. This is relevant in stimulating an active lifestyle for
35 those with a disability.

36 **Keywords:** *Pushrim kinematics, comfortable speed, pushing economy, wheelchair*
37 *exercise, gender*

Introduction

38 Differences in gait parameters between the sexes have been reported during walking
39 (Cho, Park, & Kwon, 2004). Additionally, psychophysical measures such as rating of
40 perceived exertion (RPE) were found to be related to changes in walking speed (Chiu
41 and Wang, 2007), where women demonstrated a higher local RPE than men in their
42 lower back and rear thigh during normal walking speed (0.83 m/s - 1.38 m/s). Clearly,
43 relevant differences exist in gait biomechanics and perceived psychophysiological
44 measures between men and women. The same may be true for a different form of daily
45 mobility relevant for those with a disability: wheelchair propulsion. However, sex
46 differences in wheelchair propulsion biomechanics, psychophysical measures and

47 comfortable speed have yet to be established. Most studies have been conducted in a
48 male population, and not much is known about female-specific propulsion
49 characteristics.

50 American census data showed that 58.84% (or 941,000 persons) of the total
51 wheelchair user population were women (Kaye, Kang, & LaPlante, 2000). About
52 100,000 persons were young women aged in the range of 18-44 years (Kaye, et al.,
53 2000). The number of women wheelchair users is expected to increase even more with
54 the growing of the ageing population and the further increase in incidence of women
55 with spinal cord injury (SCI), from 18.2% in 1980 to 20% in 2016 ("Spinal Cord Injury
56 (SCI) 2016 Facts and Figures at a Glance," 2016). It has been well documented that
57 women tend to be smaller in body size and weaker in muscle strength than men in both
58 the SCI population as well as in the able-bodied population (Fay, Boninger, Cooper,
59 Koontz, & Fitzgerald, 2000; Nicholas, Robinson, Logan, & Robertson, 1989). In
60 persons with a SCI, shoulder torque was found to be 62%–96% lower in women than in
61 men (Hatchett et al., 2009; Souza et al., 2005). Additionally, women have shorter upper
62 extremities relative to their body length with narrower shoulder girdles compared to
63 men (Boninger et al., 2003; Schultz, Lee, & Nance, 2001). These anthropometrical
64 characteristics result in a biomechanical disadvantage for upper extremity activities
65 leading to a high repetitive load on the shoulder joint (Boninger, et al., 2003; Hatchett,
66 et al., 2009). Hence, the unique upper extremity structure of women accompanied by
67 weaker muscles associated with a higher incidence of shoulder pain than observed in
68 men engaging in the same levels of physical activities (Andersson, Ejlertsson, Leden, &
69 Rosenberg, 1993). Although these sex differences in anthropometrics and strength
70 between men and women have been established (Schultz, et al., 2001; Souza, et al.,

71 2005), the potential impact of these differences on wheelchair propulsion biomechanics
72 is unclear. The present study aimed to investigate the differences between novice young
73 able-bodied men and women and how this impacted on propulsion speed, propulsion
74 biomechanics, force effectiveness, mechanical efficiency and psychophysical
75 parameters. Able-bodied individuals were selected to compare results of homogenous
76 groups of men and women, and to eliminate unknown effects of different disabilities
77 into the outcome parameters.

78 **Methods**

79 *Participants*

80 Thirty men (mean age: 26 ± 4 years, height: 1.75 ± 0.07 m, mass: 73.7 ± 13.4 kg) and
81 30 women (mean age: 27 ± 5 years, height: 1.62 ± 0.07 m, mass: 59.2 ± 12.7 kg). The
82 participants were recruited using volunteer and convenient sampling method. Inclusion
83 criteria were: 18-40 years, 150 - 190 cm tall, less than 90 kg of body mass to fit the
84 wheelchair used (MacPhee, Kirby, Bell, & MacLeod, 2001), inexperienced in
85 wheelchair use, absence of any musculoskeletal problems. An additional inclusion
86 criterion was the ability to fit in the study wheelchair of width 0.42m. All participants
87 completed a PAR-Q questionnaire and gave written informed consent prior to
88 participation. Approval for the project was obtained from the University of Essex Ethics
89 Committee.

90 *Experimental Design*

91 All participants were given 12-minute familiarization as described by Vegter et al.
92 (2014): four 3-minute over-ground familiarization blocks to roll a wheelchair over
93 ground in a straight-line at their comfortable speed (CS) with a 2-minute break between

94 blocks were completed (Vegter, de Groot, Lamothe, Veeger, & van der Woude, 2014).
95 After familiarization, participants performed two trials of 10 seconds of over-ground
96 propulsion at their CS. The comfortable speed from the averaged two trials was used for
97 further testing on the treadmill. A further 5-minute familiarization was conducted on the
98 treadmill with 8-minute subsequent recovery as described by previous studies
99 (Kwarciak, Turner, Guo, & Richter, 2011), followed by the 3 x 4-minute submaximal
100 wheelchair tests in the standardized wheelchair instrumented with a Smart^{wheel} (Three
101 Rivers Holdings, Arizona, USA) on the treadmill to investigate propulsion kinetics
102 (torque produced at the hub; M_z , effective or tangential force; F_t and total force applied;
103 F_{tot}), timing parameters (push percentage, push frequency, push time, cycle time, and
104 push angle) and efficiency parameters (fraction of effective force; FEF, net efficiency;
105 NE and gross mechanical efficiency; GE). The submaximal tests were conducted at CS,
106 125% of CS and 145% of CS with 8 minutes of rest between trials.

107 Resting oxygen consumption ($\dot{V}O_{2rest}$) was collected by CPX (Jaeger,
108 Hoechberg, Germany). During each trial, HR (Polar Electro, Kempele, Finland) and
109 $\dot{V}O_2$ (Jaeger, Hoechberg, Germany) were continuously measured. After each trial,
110 participants were immediately asked to report their perceived exertion of the whole
111 body using the 15-point Borg scale of perceived exertion (central RPE 15) (Borg, 1970)
112 and the perceived exertion of the arm and shoulder area by the 10-point scale for local
113 perceived exertion (L-RPE 10) (Borg, 1982).

114 The timing parameters were determined from the torque signal as done in De
115 Groot et al. (2003) (De Groot, Veeger, Hollander, & Van der Woude, 2003). The push
116 frequency was defined as the number of pushes per minute. The push time was defined
117 as the time duration that the hand applied a positive torque on the hand rim. The cycle

118 time was defined as the amount of time from the onset of one push phase to the onset of
119 the next. The push angle was defined as angle at the end of the push minus the angle at
120 the start. The push phase was expressed as a percentage of the cycle time (%push phase)
121 (De Groot, et al., 2003; Vegter, Lamoth, De Groot, Veeger, & Van der Woude, 2013).
122 FEF was defined as the ratio between the magnitude of F_{tot} and F_t and expressed as a
123 percentage, see Equation 1. GE was defined as the percentage of energy input that
124 appears as useful external work, see Equation 2. In NE, energy expended was corrected
125 for resting metabolism, see Equation 3.

126 *Experimental protocol*

127 The submaximal wheelchair test was performed in a standardized wheelchair. A
128 non-folding ultra-light wheelchair (Quickie, USA) (seat height: 0.50m; diameter of the
129 wheels: 0.64m; chair width: 0.42m; chair depth 0.41m) was mounted with a force- and
130 torque-sensing SMART^{Wheel} (3 Rivers Holdings, Mesa, AZ) to the right wheel to collect
131 kinetic data (mass of 4 kg, wheel diameter of 0.64 m and handrim diameter of 0.56m)
132 with a mass-matched dummy wheel on the left side. The total mass of the wheelchair
133 was 14 kg.

134 Participants completed the familiarization sessions over ground and on the
135 motor-driven treadmill (Saturn, HP-Cosmos, Nussdorf, Germany, 1.0 x 2.7 m) and
136 comfortable speed was determined. Once the familiarization period was completed,
137 participants were given 8 minutes to rest. After an 8-minute resting period, participants
138 were asked to propel the wheelchair on the driven-motor treadmill as naturally as
139 possible at three randomly imposed speeds: CS, 125% and 145% of CS. Each exercise
140 bout lasted 4 minutes with an 8- minute rest interval to allow for HR to return close to

141 their baseline. Participants did not receive any instructions on wheelchair propulsion
142 style.

143 Oxygen consumption and HR were continuously collected during the trials.
144 Kinetic data and physiological outcomes were calculated as an average value over 20
145 seconds of the steady state of the last minute. The last minute was used to evaluate
146 physiological outcomes to ensure the steady-state oxygen consumption during
147 wheelchair propulsion as described in previous studies (J. Lenton et al., 2013; Yang,
148 Koontz, Triolo, Cooper, & Boninger, 2009). The total force (F_{tot}) and the tangential
149 force (F_t) were calculated and derived from the SMART^{Wheel} (Cooper, Robertson,
150 VanSickle, Boninger, & Shimada, 1997). FEF was calculated and expressed as the time
151 average FEF over the 20-min measurement period:

$$152 \quad FEF = F_t \cdot F_{tot}^{-1} \cdot 100 (\%) \quad (1) \text{ (Veeger, Van der Woude, \&} \\ 153 \quad \text{Rozendal, 1991)}$$

154 GE and NE were obtained. GE was calculated as the ratio of the external work
155 to the metabolic energy expended during exercise. External work done was determined
156 from the mean power output (PO_{mean}) values derived from the SMART^{Wheel} during the
157 handrim wheelchair propulsion for all speeds. GE was obtained during submaximal
158 wheelchair exercise and calculated as the ratio between PO_{mean} and total metabolic
159 production of energy during exercise (En). Where En was calculated by multiplying
160 oxygen uptake with the oxygen equivalent according to Garby and Astrup (Garby and
161 Astrup, 1987).

$$162 \quad GE = PO_{mean} / En \cdot 100 (\%) \quad (2) \text{ (Whipp and Wasserman,}$$

163 1969)

164 Secondly, NE was calculated, an efficiency measure in which the energy expended
165 during exercise was corrected for resting metabolism (Er).

166
$$NE = PO_{\text{mean}} / (E_n - E_r) \cdot 100 (\%) \quad (3) \text{(Whipp and Wasserman,}$$

167 1969)

168 The 15-point Borg scale of perceived exertion (central RPE 15) was applied to assess
169 the rate of perceived exertion, where 6 represents ‘extremely light’ and 20 represents
170 ‘extremely hard’ (Borg, 1970). The 10-point scale for local rate of perceived exertion
171 (local RPE 10) was used to assess the feelings of exertion experienced at arms and
172 shoulders, where 0 represents ‘nothing at all’ and 10 represents ‘extremely hard’ (Borg,
173 1982). Both RPE scales were reported immediately after each trial.

174 *Statistical analyses*

175 The data were analyzed using the Predictive Analytics Software (SPSS for Mac Version
176 19; SPSS Inc., Chicago, USA). Standard descriptive statistics (mean with standard
177 deviations) were calculated for all variables. An independent t-test was performed to
178 compare sex differences in demographic data and comfortable speed. A mixed analysis
179 of variance (ANOVA) was applied to compare timing parameters, efficiency outcomes,
180 HR and RPE between in men and women in the three submaximal wheelchair
181 propulsion bouts. When a difference was found, a Bonferroni post hoc test adjusted for
182 multiple comparisons were conducted to determine the sex and speed, which were
183 significantly different from each other. A statistical significance level was set at $p <$
184 0.05.

185 **Results**

186 *Resting heart rate and oxygen consumption*

187 No significant differences in HR_{rest} (men 73.23±9.69 beats.min⁻¹; women 78.20±10.70
188 beats.min⁻¹; p = 0.065) and resting $\dot{V}O_2$ (men 4.62±1.00 ml/kg.min; 4.58±1.15
189 ml/kg.min; p = 0.86) were found between men and women.

190 *Comfortable speed*

191 The results showed comfortable speed for men was faster (0.98 ± 0.24 m/s) compared to
192 women (0.71 ± 0.18 m/s) (p < 0.001).

193 *Timing parameters*

194 Comparisons of timing parameters obtained during CS, 125% of CS and 145% of CS
195 between groups are shown in Table I. There was a significant (p < 0.001) speed effect
196 for push percentage. There was a significant (p = 0.001) sex effect for push percentage
197 whereby: men exhibited a significant lower push percentage than women at CS (p =
198 0.001), 125% of CS (p = 0.002) and 145% of CS (p = 0.005). No significant interactions
199 between speed and sex (p = 0.865) were found for push percentage. There was a
200 significant (p = 0.007) speed effect for push time. No significant sex effect and
201 interactions between speed and sex for push time were found (p >0.05).

202

203 *Please insert table I about here*

204

205 There was a significant (p < 0.001) speed effect for push angle. There was a
206 significant (p = 0.003) sex effect for push angle: men exhibited a significantly greater
207 push angle than women at CS (p = 0.003), 125% of CS (p = 0.008) and 145% of CS (p

208 = 0.009). No significant interactions between speed and group were observed for push
209 angle ($p = 0.09$). No significant main effects and interactions for push frequency and
210 cycle time were detected.

211 *Efficiency outcomes*

212 Means and standard deviations of the efficiency outcomes at CS, 125% of CS and 145%
213 of CS are shown in Table II. There were no significant sex effects and interaction
214 effects between speed and sex for FEF and NE. There was a significant ($p < 0.001$)
215 speed effect for GE. There was a significant ($p < 0.05$) sex effect for GE with a
216 significantly higher GE in men than women at CS ($p = 0.012$), at 125% of CS ($p =$
217 0.038) and at 145% of CS ($p = 0.006$). No significant interactions between speed and
218 sex were found ($p = 0.66$).

219

220 *Please insert table II about here*

221

222 *Heart rate and Psychophysiological parameters*

223 Means and standard deviations of HR during the final minute of propulsion, as well as
224 central RPE and local RPE of the three trial speeds for men and women, are presented
225 in Table III. There was a significant ($p < 0.001$) speed effect for HR. Men showed HR
226 increased significantly between CS and 145% of CS ($p = 0.025$). Women showed HR
227 increased significantly between CS and 125% of CS ($p = 0.003$), between CS and 145%
228 of CS ($p < 0.001$), and between 125% of CS and 145% of CS ($p < 0.001$). There was no

229 significant main effect for sex ($p = 0.727$) and interaction between speed and sex ($p =$
230 0.075) for HR.

231

232 *Please insert table III about here*

233

234 There was a significant ($p < 0.001$) speed effect for central RPE. No significant
235 main effect for sex ($p = 0.686$) and no interaction between speed and sex ($p = 0.19$) for
236 central RPE were found.

237 There were significant main effects ($p < 0.001$ and $p < 0.05$ for speed and sex,
238 respectively) and interactions between speed and sex for local RPE. Bonferroni
239 corrected post hoc tests showed that both groups experienced a significant increase in
240 local RPE between CS and 125% of CS ($p < 0.001$), and between CS and 145% of CS
241 ($p < 0.001$), and between 125% of CS and 145% of CS ($p < 0.001$); both men and
242 women showed local RPE at CS was significantly lower than at 125% ($p < 0.05$) and at
243 145% of CS ($p < 0.001$) and local RPE at 125% of CS was significantly lower than
244 145% of CS ($p < 0.05$). Women exhibited a significantly higher local RPE than men at
245 CS ($p < 0.001$), 125% of CS ($p < 0.001$) and at 145% of CS ($p < 0.001$).

246 **Discussion**

247 The novice finding of the present study in novice young-able-bodied participants was
248 that sex differences seem to exist in wheelchair propulsion. Men exhibited a faster
249 comfortable propulsion speed compared to women. Interestingly, even though their
250 propulsion speeds were lower, women rated their local perceived exertion higher, and
251 demonstrated a lower GE compared to men. Sex-dependent differences were also found

252 in propulsion characteristics. Men demonstrated a lower push percentage, a lower push
253 frequency and a higher push angle compared to women. The demonstrated sex
254 differences in propulsion characteristics seem to be relevant for clinical applications.
255 More awareness of these differences might be needed, for example for appropriate
256 wheelchair fitting and appropriate design of exercise programs and the development of
257 optimal propulsion instructions in rehabilitation.

258 Comfortable speed in this study was comparable to those reported in the
259 previous able-bodied studies (0.75 m/s – 0.98 m/s) (Hers, Sawatzky, & Sheel, 2016;
260 Robertson, Boninger, Cooper, & Shimada, 1996). The present study demonstrated that
261 women propelled themselves at lower comfortable propulsion speed compared to men.
262 This can be explained by women bearing a shoulder strength deficit (Schultz, et al.,
263 2001) coupled with a propulsion biomechanical disadvantage due to a shorter humerus
264 bone relative to body length and a narrow shoulder girdle (Boninger, et al., 2003;
265 Hatchett, et al., 2009). Muscular strength and anthropometric measures are greatly
266 dependent on sex. Additionally, based on their relatively smaller body mass, women
267 were propelling a proportionally heavier wheelchair. The 14-kg wheelchair was 24% of
268 women's body mass compared to 19% of men's body mass. These could contribute to
269 sex differences in comfortable propulsion speed and its characteristics, resulting in
270 differences in PO and kinetic parameters. Based on these findings, propulsion
271 biomechanics of men and women should be analyzed separately in wheelchair
272 propulsion studies.

273 The greater feeling of physical effort (L-RPE) in women during wheelchair
274 propulsion, even at their comfortable speed, might be associated with the higher

275 incidence of shoulder pain compared to men engaging in the same levels of physical
276 activities in both able-bodied and SCI population (Andersson, et al., 1993; Gutierrez,
277 Newsam, Mulroy, Gronley, & Perrey, 2005). It could be implied that at the same
278 relative wheelchair propulsion speeds, women demonstrate a greater relative
279 contribution of the muscles around the shoulder joint. As mentioned earlier, women
280 propelled a proportionally heavier wheelchair to their body weight coupled with the
281 relative strength deficit of rotator cuff muscles (Hatchett, et al., 2009), it is therefore not
282 surprising that local RPE was higher compared to men. In the present study, the very
283 low local RPE of men was comparable to those reported in the previous studies (Qi,
284 Ferguson-Pell, Salimi, Haennel, & Ramadi, 2015). Our study was the first to report the
285 local RPE of women during comfortable speed, at 5 or 'hard' level.

286 Mechanical efficiency indices reflect efficiency and economy of wheelchair
287 propulsion. The values of mechanical efficiency were reported to vary between 5-16%
288 for NE (Hintzy and Tordi, 2004; Knowlton, Fitzgerald, & Sedlock, 1981; J. P. Lenton,
289 Fowler, Van der Woude, & Goosey-Tolfrey, 2008) and 2-1(Mason, Lenton, Leicht, &
290 Goosey-Tolfrey, 2014)1% for GE in able-bodied and SCI individuals (De Groot, De
291 Bruin, Noomen, & Van der Woude, 2008; Hers, et al., 2016; J. Lenton, et al., 2013; J. P.
292 Lenton, et al., 2008; Van der Woude, Veeger, Dallmeijer, Janssen, & Rozendaal, 2001;
293 Vanlandewijck, Theisen, & Daly, 2001; Veeger, et al., 1991; Yang, et al., 2009).
294 Consistent with the literature, both groups of the present study demonstrated that NE
295 ranged around 8.6% -10.6% and GE varied 4.1%-6.3% across the three speeds. We
296 found that men performed wheelchair propulsion more efficiently (GE) compared to
297 women across the three speeds. The difference in GE between men and women also
298 supports the hypothesis of previous studies that GE of wheelchair propulsion depends

299 on user characteristics (De Groot, et al., 2008; Medola, Elui, da Silva Santana, &
300 Fortulan, 2014). However, it needs to be noted that men performed at higher velocities,
301 and higher absolute exercise intensities were found to be associated with a higher
302 efficiency (Moseley and Jeukendrup, 2001) due to the lower relative contribution of
303 resting metabolism at higher velocities. When looking into NE, an efficiency parameter
304 that corrects gross-efficiency for the relative contribution of basal metabolism (Moseley
305 and Jeukendrup, 2001), no differences were found between sexes. This suggests that the
306 lower gross-efficiencies found for women are associated with their lower propulsion
307 velocities.

308 Push frequency is considered an important timing parameter of wheelchair
309 propulsion. Push frequency at CS in this study was in agreement with the literature, 55-
310 70 pushes/min (De Groot, et al., 2008; Hers, et al., 2016; J. Lenton, et al., 2013). Our
311 finding showed that women propelled themselves with a higher frequency and a less
312 push angle. This implies that an increased push frequency increases muscle contraction
313 and energy expended, leading to a significantly higher local RPE found in women
314 compared to men (Goosey-Tolfrey and Kirk, 2003). Our study showed push angles of
315 30° - 45° in accordance with the push angle in the literature, ranged 22° - 45° (Mason,
316 et al., 2014; Rudins, Laskowski, Grownney, Cahalan, & An, 1997). Push angle in men
317 was significantly higher compared to women across the three speeds. Higher push angle
318 in men might be due to anatomical and biomechanical advantage (Boninger, et al.,
319 2003; Fay, et al., 2000; Hatchett, et al., 2009). Push percentages of 24% - 32% over the
320 three speeds in the present study were consistent with the literature, ranging between
321 25% and 40% of the total cycle (J. Lenton, et al., 2013; Shimada, Robertson,
322 Bonninger, & Cooper, 1998; Vanlandewijck, et al., 2001). Push percentage was

323 significantly higher in women across the three speeds. Sex differences in
324 anthropometric and physiologic data may contribute to differences in push angle and
325 push percentage between men and women. In women, shorter arms, narrower shoulders
326 and a shorter torso (Schultz, et al., 2001) could result in increased elbow flexion,
327 increased shoulder extension and increased shoulder abduction while gripping the top
328 dead centre of the handrims. These joint positions would limit push arc range, decrease
329 push angle and lower propulsion efficiency (Kotajarvi et al., 2004; Richter, 2001).
330 Brubaker et al. (1984) noted that users with longer arms demonstrated an increase in
331 propulsion efficiency over those users with shorter arms (Brubaker, McClay, &
332 McLaurin, 1984). Push angle was also found to be affected by the horizontal seat
333 position relative to the users total arm length (Hughes, Weimar, Sheth, & Brubaker,
334 1992). In the present study, higher push percentage and increased push time in women
335 may be also related to smaller muscles with a greater proportional area of type I fibres
336 resulting in slower contraction velocity and decreased power compared with men
337 (Hunter, 2014).

338 An analogy with gait can be seen where women walk slower but with a higher
339 step frequency and shorter step length compared to men (Bohannon, 1997). It has been
340 suggested that walking with shorter steps and a higher step frequency could increase
341 compressive loading to the joints, placing women at the high risk of lower limb injuries
342 (Hunt, Birmingham, Giffin, & Jenkyn, 2006). In the same way, a higher push frequency
343 with shorter push angle in wheelchair propulsion may cause women to experience
344 greater shoulder pain and injury (Boninger, et al., 2003). Lenton et al. speculated that a
345 decreased push frequency could be contributing to lowered intramuscular pressure
346 along with a decreased oxygen transport resulting in improved efficiency and reduced

347 shoulder pain (J. Lenton, et al., 2013).

348 Based on the reported sex differences, we suggest that women should receive
349 more specific attention regarding their physical capacity, propulsion speed and
350 propulsion technique as well as wheelchair selection. Lighter weight wheelchairs may
351 be more suitable for women's functional features because they are easier to operate and
352 less force is required (DiGiovine et al., 2000; Medola, et al., 2014). This could help to
353 reduce mechanical load and the risk of developing upper extremity injuries in women
354 users (Medicine, 2005). To prescribe wheelchair training or exercise, or any
355 intervention to women, experts should be considering the difference in psychophysical
356 responses to wheelchair propulsion between men and women. Our findings also
357 enhance better understanding of wheelchair propulsion efficiency in men and women.
358 More importantly, awareness of sex differences may aid in optimizing wheelchair
359 propulsion through proper training and advice to prevent injuries and improve
360 performance.

361 There are limitations to the present study. Firstly, the use of the same
362 standardized ultra-light wheelchair (Quickie, USA) without individual adjustments
363 relative to anthropometrics of the participants could be a limitation, as a proper fit of the
364 manual wheelchair to the user has been found to be important for optimal wheelchair
365 propulsion (Kotajarvi, et al., 2004). However, the literature in able-bodied novice users
366 has consistently used the similar non-adjustable wheelchair to all participants to
367 evaluate kinetics and efficiency outcomes during wheelchair propulsion (J. Lenton, et
368 al., 2013; Mason, et al., 2014) and using the standardized wheelchair configuration has
369 as benefit that it excludes the impact of different wheelchair setups on physiological and

370 biomechanical parameters (Kotajarvi, et al., 2004). As the aim of this study was to
371 investigate the impacts of sex on speed, kinetics and psychophysiology of wheelchair
372 propulsion, it was crucial to eliminate any bias caused by wheelchair model/setup.

373 Secondly, we chose to include able-bodied participants. This leads to a
374 homogenous group of subjects, where differences between severity and type of
375 disability will not interfere with our data. However, it limits the transferability of our
376 results to wheelchair users, and it will be of interest to also look into sex differences on
377 wheelchair propulsion in persons with different disabilities.

378 Considering the sex differences in this study merits not only awareness of these
379 differences, but also provides useful data to be able to interpret any deviations from this
380 able-bodied pattern due to disabilities. It has also been suggested that able-bodied
381 novice wheelchair exercisers share similar features with newly injured individuals (Van
382 Den Berg, De Groot, Swart, & Van Der Woude, 2010). Therefore, our findings could
383 be, at least, transferable to the newly injured population in the initial stages of
384 rehabilitation.

385 **Conclusion**

386 Differences between men and women were found in wheelchair comfortable propulsion
387 speed, gross efficiency and several propulsion characteristics. Able-bodied young men
388 demonstrated a faster comfortable propulsion speed, a lower push percentage and
389 greater push angle compared to the able-bodied young women. Even though their
390 propulsion speed was slower, women experienced higher locally perceived exertion
391 ratings compared to men. Awareness of these differences may aid in optimizing
392 wheelchair propulsion through proper training and advice to prevent injuries and

393 improve performance. This research can be used as a starting point to initiate more
394 specific research into gender differences in different disability groups, and will be
395 relevant in stimulating an active lifestyle for those with a disability.

396

397 **Disclosure statement**

398 No potential conflict of interest was reported by the authors.

399

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403

404

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571

Table I. Mean values \pm SD of the timing parameters at CS, 125% and 145% of CS for men and women

| Variable | Sex | Speed | | | Post hoc |
|--|-----|-------------------|-------------------------------|----------------------------------|--------------|
| | | CS | 125% | 145% of CS | |
| Push percentage [%cycle] ^{a,b,c,d,e,f} | M | 26.63 \pm 5.71 | 25.04 \pm 5.65 | 23.82 \pm 6.29 [*] | CS>125%, |
| | W | 32.01 \pm 6.09 | 30.00 \pm 6.00 [*] | 28.65 \pm 6.60 [*] | CS>145% |
| Push frequency [pushes/min] | M | 63.70 \pm 18.12 | 65.30 \pm 24.63 | 66.50 \pm 22.98 | - |
| | W | 70.60 \pm 23.45 | 74.60 \pm 23.63 | 74.60 \pm 23.26 | - |
| Push time [s] ^a | M | 0.27 \pm 0.09 | 0.25 \pm 0.08 | 0.25 \pm 0.12 | CS>125%, |
| | W | 0.30 \pm 0.11 | 0.26 \pm 0.09 [*] | 0.25 \pm 0.08 [*] | CS>145% |
| Cycle time [s] | M | 1.06 \pm 0.40 | 1.03 \pm 0.32 | 1.10 \pm 0.54 | - |
| | W | 0.95 \pm 0.34 | 0.93 \pm 0.40 | 0.91 \pm 0.32 | - |
| Push angle [degree] ^{a,b,d,e,f} | M | 38.61 \pm 11.97 | 41.75 \pm 11.61 | 45.16 \pm 12.93 ^{*,†} | CS<125%<145% |
| | W | 29.66 \pm 9.99 | 32.68 \pm 13.75 | 35.90 \pm 13.74 ^{*,†} | CS<125%<145% |

^a Significant main effect for Speed, ^b Significant main effect for Sex, ^c Significant interaction between Speed x Sex, ^d significant men to women pairwise comparison in CS, ^e significant men to women pairwise comparison in 125% of CS, ^f significant men to women pairwise comparison in 145% of CS, * = the value is different from CS, † = the value is different from 125% of CS, - = post hoc analysis was not performed due to non-significant main effect, M = men, W = women, CS = comfortable speed. All differences are P < 0.05.

Table II. Mean values \pm SD of efficiency outcomes (GE, NE and FEF) at comfortable speed, 125% and 145% of comfortable speed for men and women

| Variable | Sex | Speed | | | Post hoc |
|-----------------------|-----|-------------------|-------------------|-------------------------------|------------|
| | | CS | 125% | 145% | |
| FEF [%] | M | 69.27 \pm 14.68 | 69.29 \pm 11.50 | 72.32 \pm 11.73 | - |
| | W | 67.81 \pm 12.80 | 64.83 \pm 13.90 | 64.23 \pm 12.81 | |
| NE [%] | M | 9.60 \pm 3.25 | 10.48 \pm 2.97 | 10.67 \pm 3.89 | - |
| | W | 8.72 \pm 2.84 | 9.12 \pm 3.08 | 8.64 \pm 2.80 | |
| GE [%] ^{a,b} | M | 5.16 \pm 1.67 | 5.50 \pm 1.55 | 6.30 \pm 1.80 ^{*†} | 125%<145%, |
| | W | 4.14 \pm 1.34 | 4.68 \pm 1.44 | 5.12 \pm 1.36 [*] | CS%<145% |

^a Significant main effect for Speed, ^b Significant main effect for Sex, * = the value is different from CS, † = the value is different from 125% of CS, - = post hoc analysis was not performed due to non-significant main effect, M = men, W = women, CS = comfortable speed. All differences are P < 0.05.

Table III. Mean values \pm SD of the heart rate (beats.min⁻¹), the central rate of perceived exertion (Central RPE 15) and the local rate of perceived exertion (Local RPE 10) after completion of the exercise bouts for the men and women

| Variable | Sex | Speed | | | Post hoc |
|--|-----|-------------------|---------------------|----------------------------------|--------------|
| | | CS | 125% | 145% | |
| HR [beats.min ⁻¹] ^a | M | 97.18 \pm 16.96 | 100.55 \pm 16.16 | 104.52 \pm 17.81* | CS<125%<145% |
| | W | 95.07 \pm 25.09 | 102.47 \pm 19.83* | 109.83 \pm 23.01* [†] | |
| Central RPE15 ^a | M | 9.93 \pm 2.12 | 10.93 \pm 2.12* | 12.33 \pm 2.73* [†] | CS<125%<145% |
| | W | 9.93 \pm 2.45 | 10.83 \pm 2.74* | 11.67 \pm 3.21* [†] | |
| Local RPE10 a,b,c,d,e,f | M | 2.82 \pm 1.83 | 3.48 \pm 2.05* | 4.50 \pm 2.13* [†] | CS<125%<145% |
| | W | 5.50 \pm 1.89 | 6.10 \pm 2.02* | 6.85 \pm 2.31* [†] | |

^a Significant main effect for Speed, ^b Significant main effect for Sex, ^c Significant interaction between Speed x Sex, ^d significant men to women pairwise comparison in CS, ^e significant men to women pairwise comparison in 125% of CS, ^f significant men to women pairwise comparison in 145% of CS, * = the value is different from CS, † = the value is different from 125% of CS, - = post hoc analysis was not performed due to non-significant main effect, M = men, W = women, CS = comfortable speed. All differences are P < 0.05.