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**Running head:** Wheelchair propulsion over a cross-slope

**Title:** Trunk and glenohumeral joint adaptations to manual wheelchair propulsion over a cross-slope: an exploratory study

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# **Trunk and glenohumeral joint adaptations to manual wheelchair propulsion over a cross-slope: an exploratory study**

## **ABSTRACT**

**Background:** Cross-slopes are often encountered by manual wheelchair users propelling within an urban setting. While propulsion over cross-slopes is more difficult than on level surfaces, little is known about how the users counter the downhill turning tendency of the wheelchair over cross-slopes. This study aimed to identify the adaptations of the manual wheelchair users to the presence of cross-slopes and examine how these might impact shoulder injury.

**Methods:** Nine manual wheelchair users propelled themselves across a cross-slope and over a level surface. The trunk and glenohumeral joint kinematics, as well as the handrim contact tangential force were compared between both conditions for the uphill and downhill limbs.

**Findings:** The uphill arm technique used to counter the downhill turning tendency varied greatly in terms of potential injury risk and efficiency between participants. Trunk flexion increased the turning tendency of the manual wheelchair, yet only one participant decreased his flexion when rolling over the cross-slope. Various potential pathomechanisms related to the trunk lateral flexion and the glenohumeral kinematics over a cross-slope were identified.

**Interpretation:** Both the uphill arm technique and trunk kinematics are important to propel over a cross-slope both efficiently and safely. Accordingly, tips about posture and kinematics are needed to teach this skill to manual wheelchair users. Additionally, as wheelchair positioning seems to influence the cross-slope skill, more research is needed to explore the impact of positioning devices (e.g., lateral supports) and wheelchair modifications (e.g., power assist wheels, handrim projections) on this skill.

**Keywords:** Wheelchair propulsion; Cross-slope; Glenohumeral joint; Trunk; Wheelchair skills.

## 1 INTRODUCTION

2 The quality of life and the health of manual wheelchair users (MWUs) are associated with  
3 their participation.<sup>1</sup> Pain and wheelchair skills are two frequently reported modifiable factors  
4 that influence social participation.<sup>2-4</sup> Within an urban setting, MWUs will frequently  
5 encounter cross-slopes. Indeed, roads and sidewalks alike are slightly sloped to help water  
6 drainage. As MWUs propel themselves over a cross-slope, their wheelchair will tend to turn  
7 downhill due to the moment generated by the weight of the manual wheelchair and its user.<sup>5</sup>  
8 While there is a consensus that cross-slope propulsion is more difficult than propulsion over a  
9 level surface,<sup>6</sup> little information on its impact on the MWU can be found in the literature.<sup>6,7</sup>  
10 Brubaker et al. found that the presence of a 2° cross-slope roughly doubled the drag at similar  
11 velocities, increasing the propulsion energy cost and oxygen consumption.<sup>5</sup> The propulsion  
12 speed seems to decrease, particularly due to the decrease in the distance traveled per push.<sup>8</sup>  
13 Peak handrim force, rate of loading, and axial moment measured for the downhill wheel were  
14 reported to increase with the cross-slope angle.<sup>8</sup> On the other hand, the uphill wheel was  
15 reported to have a negative mechanical power as it regulates the wheelchair trajectory.<sup>9</sup> As the  
16 amplitude of handrim forces, the rate of loading and shoulder kinematics are correlated with  
17 musculoskeletal injury,<sup>10-12</sup> the increased asymmetry and biomechanical load<sup>9,13</sup> observed for  
18 cross-slope propulsion might increase musculoskeletal injury. Thus, this skill requires specific  
19 training of the MWUs to insure a safe and efficient technique.<sup>14</sup> Nevertheless, we could not  
20 find studies that gave recommendations about cross-slope propulsion technique.

21 The Wheelchair Skills Program<sup>14</sup> (WSP) includes cross-slope propulsion as an individual skill  
22 often encountered in the user's environment. According to the WSP, MWUs should keep their  
23 weight off the caster wheels by leaning backward. To avoid the downward turning tendency,  
24 they should push harder and/or more frequently on the downhill handrim. The WSP states that  
25 the uphill hand can be solely used for braking in some cases.

26 Considering these recommendations and the lack of studies evaluating the propulsion across a  
27 cross-slope, we aimed to identify the adaptations of the MWUs to the presence of a cross-  
28 slope and then to discuss them in light of the WSP recommendations. A secondary objective  
29 was to evaluate the potential additional risk of shoulder injury associated with cross-slope  
30 propulsion.

## 31 **METHODS**

### 32 *Study design*

33 This is a cross-sectional exploratory study. The research protocol was approved by the Sainte-  
34 Justine University Hospital Center Ethics Committee (MP-21-2020-2533). All participants  
35 provided their written informed consent before the experimentation.

### 36 *Participants*

37 A sample of convenience was recruited from the *Institut universitaire sur la réadaptation en*  
38 *déficience physique de Montréal*. Interested individuals were included in this study if they had  
39 been using a manual wheelchair for mobility for 6 months to 8 years and were 20- to 40-year-  
40 old active MWUs with no neurodegenerative disorders. We confirmed that the participants  
41 had no history of shoulder pathology based on their self-report.

### 42 *Experimental Setup*

43 To track the trunk and the right upper limb, 38 reflective skin markers were used. Sixteen  
44 additional markers were placed on the wheelchair frame (6) and rear wheels (2x5).  
45 Kinematics were recorded using a motion capture system (Vicon Motion Systems, Oxford,  
46 UK) at 250 Hz. Muscle activity was recorded using bipolar surface EMG electrodes (Delsys,  
47 Natick, USA) for 11 muscles: deltoids (anterior, median, and posterior), trapezius (upper,  
48 middle, and lower), serratus anterior, latissimus dorsi, pectoralis major (clavicular head),  
49 biceps, and triceps (long and lateral). Additionally, for consenting participants, indwelling

50 electrodes were inserted into the supraspinatus, infraspinatus, and subscapularis. EMG signals  
51 were collected at 2000 Hz. Each participant's wheelchair was fitted with a Smart<sup>wheel</sup> (Three  
52 Rivers Holdings LLC, Mesa, USA) on its right side that measured handrim kinetics at 240 Hz.

### 53 *Procedure*

54 The participants first propelled their wheelchair at a comfortable speed over a level surface. A  
55 wooden platform (4.5 m length, 1.2 m width) was used to simulate a 5° cross-slope. The  
56 cross-slope angle was chosen based on the set-up used in the Wheelchair Skills Test.<sup>15</sup> After  
57 getting familiar with the set-up, the participants propelled themselves at a comfortable speed  
58 in both directions (right arm on the downhill and uphill of the slope, Fig. 1). They were  
59 instructed to maintain a straight-line trajectory. Each condition was repeated four times.

60 – Insert Figure 1 here –

### 61 *Additional measures*

62 The details of participants' wheelchairs were logged, as well as the horizontal position of the  
63 acromion with respect to the rear wheel axle. Shoulder pain was evaluated using the  
64 WUSPI<sup>16</sup>. Neer's<sup>17</sup> and Hawkins-Kennedy<sup>18</sup> tests were used to check for impingement.  
65 Rotator cuff tears were assessed using an external rotation lag sign<sup>19</sup> and a Napoleon test<sup>20</sup>.  
66 Additionally, participants completed a Wheelchair Skills Test (WST)<sup>15</sup>. By interview and self-  
67 reported forms, we recorded the daily activities of participants, their major mobility  
68 limitations when using a wheelchair, as well as their opinion about cross-slope propulsion.

### 69 *Analysis*

70 The EMG raw signals were first processed using a fourth-order bandpass filter (20 to 500 Hz  
71 and 600 Hz for intra-muscular), then full wave rectified. The envelopes were extracted using a  
72 4 Hz low-pass filter, then normalized to recorded maximal voluntary contractions (MVC).  
73 During the MVCs, the participants increased their activation for 3 seconds before maintaining

74 their MVC for 3 seconds under verbal encouragement. The MVCs were 1 min apart unless the  
75 participant required more rest time. For all participants, trunk stability was ensured  
76 throughout the MVC. The MVC trials<sup>21</sup> are presented in Table 1. Muscles have been grouped  
77 into three categories. The anterior group muscle included the anterior deltoid, the clavicular  
78 head of the pectoralis major as well as the serratus anterior. The posterior group consisted of  
79 the posterior deltoid, the latissimus dorsi and the trapezius (upper, middle and lower heads).  
80 Finally, the rotator cuff encompassed the infraspinatus, supraspinatus and subscapularis.

81 – Insert Table 1 here –

82 An Opensim<sup>22</sup> generic model<sup>23</sup> of the trunk and shoulder was scaled to each participant's  
83 anthropometry, then supplemented with a basic wheelchair model (frame and two rear  
84 wheels). The glenohumeral joint was defined as a ball and socket joint. The joints and  
85 wheelchair kinematics were calculated using a least-square inverse kinematics approach<sup>22</sup>.  
86 The wheelchair trajectory over the cross-slope was calculated to evaluate how well the  
87 participants complied with the instructions. The wheelchair velocity was calculated. The  
88 handrim kinetics were first corrected to cancel inaccuracies related to the wheel camber<sup>24</sup>. The  
89 tangential contact forces at the handrim were reported for the downhill and uphill cross-slope  
90 propulsion. The trunk orientation with respect to the wheelchair was calculated, as well as the  
91 distance between the wheelchair axle and the trunk and upper right-limb center of mass  
92 ( $d_{COM-axle}$ ). This distance represents the wheelchair rotation moment arm around the  
93 instantaneous axis of rotation orthogonal to the cross-slope plane. Thus, the bigger the  
94 distance, the larger the wheelchair downslope rotation tendency. To account for the difference  
95 in wheelchair settings between the participants, the  $d_{COM-axle}$  at the resting position was  
96 subtracted from the  $d_{COM-axle}$  during propulsion. The glenohumeral flexion, abduction and  
97 axial rotation were also reported, as well as the elbow flexion. All were compared to their

98 mean values over a level surface. All data analysis was done using Pandas<sup>25</sup> and Numpy<sup>26</sup>  
99 Python libraries.

## 100 **RESULTS**

101 Nine MWUs participated in this study (Table 2). All participants had spinal cord injuries of  
102 grade A or B in the ASIA scale.<sup>27</sup> All participants tested negative for impingement and rotator  
103 cuff tears. They reported low levels of shoulder pain (<40%) present mostly during  
104 wheelchair mobility. All tetraplegic participants used push cuffs. When asked in general about  
105 obstacles in urban mobility, none of the participants explicitly spoke about cross-slopes.  
106 However, when asked specifically about cross-slopes, P1, P4 and P6 mentioned no particular  
107 difficulty, while the others found the skill demanding, with P3 describing it as uncomfortable.  
108 To mitigate this difficulty, P2 and P7 mentioned switching the sidewalk side, while P9 stated  
109 using bike paths when available. Despite the differences in self-reported exertion related to  
110 cross-slopes, all participants were able to propel over a cross-slope during the WST, with  
111 various success levels: P1, P6, and P9 had trouble maintaining their propulsion direction, P5  
112 had disparate abilities depending on the direction, and P8 applied too much force as his caster  
113 wheels lost contact with the ground intermittently. This variability in skill level was also  
114 observed for the overall WST score. Finally, while having disparate wheelchair skills training,  
115 no participant recalled having training specific for the cross-slope.

116 – Insert Table 2 here –

117 P5 could not complete all cross-slopes trials as he could not counter the turning tendency  
118 sufficiently to keep his wheelchair from rolling off of the cross-slope. Additionally, his  
119 latissimus dorsi and serratus anterior EMG data were removed as the sensors lost contact  
120 intermittently due to severe lower limb spasms.

121 Participants propelled their wheelchair slower over a cross-slope (Fig. 2). Their downhill arm  
122 had a repeatable push and recovery cycle (Fig. 3). As for their uphill limb, participants'  
123 techniques established a spectrum ranging from solely braking the wheel's forward rotation  
124 (negative forces as represented by P9) to alternating pushing and braking the wheel (positive  
125 and negative forces as shown for P8).

126 – Insert Figure 2 here –

127 – Insert Figure 3 here –

128 The increased flexion of the trunk increased the  $d_{COM-axle}$  (Fig. 4-A). Only P1 had a much  
129 more extended trunk over the cross-slope. Whereas all participants showed a lateral trunk  
130 flexion to keep their trunk vertical, despite some of them not achieving the same amplitude  
131 for both sides (P3 and P5, Fig. 4-B). Participants adapted their glenohumeral kinematics  
132 differently to the cross-slope, with an overall tendency to increase the glenohumeral extension  
133 and adduction over the cross-slope, as well as the internal rotation for the downhill side  
134 (Fig. 5). Overall, the EMG of the anterior group increased for the downhill side, while that of  
135 the posterior group increased for the uphill one. Nevertheless, the normalized EMG level  
136 remained overall below 60% of the maximal EMG (Fig. 6).

137 – Insert Figure 4 here –

138 – Insert Figure 5 here –

139 – Insert Figure 6 here –

## 140 **DISCUSSION**

141 This exploratory study aimed to identify the adaptations of MWUs to a 5° cross-slope  
142 propulsion. Indeed, while few studies investigated cross-slope propulsion, none have

143 investigated explicitly the trunk and uphill arm adaptations. These adaptations are discussed  
144 considering the WSP recommendations in the following sections.

145 *Handrim kinetics and wheelchair trajectory*

146 Similar to Sauret et al.,<sup>9</sup> the downhill wheel led the propulsion for all participants and the  
147 uphill wheel was modulated to regulate the wheelchair trajectory. Due to the downward  
148 turning tendency of the wheelchair, a user must push harder or more often on the downhill  
149 wheel.<sup>14</sup> Participants' approaches to achieve this asymmetry varied in efficiency. Here  
150 efficiency refers to the extent to which the work produced by the uphill arm contributes to the  
151 execution of the task (*i.e.*, straight propulsion over the cross-slope). P8's technique was the  
152 least efficient, as he kept pushing the uphill wheel at each cycle, only to brake its rotation at  
153 the "recovery" phase. P8's higher handrim force input did not translate into a faster  
154 propulsion, as his propulsion velocity was comparable to that of the other participants. It is  
155 interesting to note that P8 already reported shoulder pain during mobility, after only 18  
156 months of wheelchair use. Additionally, while he scored 80% on the WST because he  
157 executed advanced skills, he rarely achieved perfect scores, likely relying on strength rather  
158 than technique. This strategy might be related to the lack of formal wheelchair skills training.  
159 P9 used his uphill arm to mainly brake the wheel. This technique is included in the WSP  
160 tips.<sup>14</sup> While it should enable the user to reduce energy expenditure to mitigate in part the  
161 difficulty of a cross-slope,<sup>5</sup> it might be problematic for tetraplegics. Indeed, tetraplegics rely  
162 on applying a large lateromedial force to compensate for their weaker grip.<sup>28</sup> Using the  
163 downhill arm solely for propulsion, and the upper one exclusively for braking, while applying  
164 high enough lateromedial forces to maintain friction between the push-cuff and the handrim,  
165 will increase the load on both limbs. As shoulder stability is compromised at high spinal cord  
166 injuries, this load would increase the strain on stabilizing muscles. Tetraplegics' difficulty to  
167 generate sufficient lateromedial force was observed when P5's arm slipped off the handrim

168 (supplementary material). This suggests the need to assist tetraplegic users through alternative  
169 strategies such as using bike paths when possible, as suggested by participants in this study.  
170 Equipment modification (e.g., assistive wheels or projection handrims) should also be  
171 investigated as a potential approach. Indeed, projection handrims would ensure control of the  
172 wheel's rotation without the necessity of relying on the lateromedial force.

173 Other participants had some uphill wheel pushes in the first half of the cross-slope. These  
174 symmetric pushes might reduce the energy needed to ensure trunk stability against the load  
175 transferred through the downhill arm.<sup>29</sup> Additional research is needed to confirm this  
176 assumption, and to evaluate the effect of downhill-push and uphill-brake technique on trunk  
177 muscles' activation levels.

#### 178 *Trunk kinematics*

179 Reducing trunk flexion over a cross-slope brought the center of mass closer to the rear wheels'  
180 axle, which would reduce the turning tendency of the wheelchair.<sup>5</sup> This is coherent with the  
181 WSP recommendations.<sup>14</sup> P1's increased trunk extension might have been particularly  
182 beneficial as her axle is set posteriorly to her acromion. As most participants' axle was  
183 anterior to their acromion, the turning moment arm was already somewhat smaller, which  
184 probably eased most participants straight propulsion despite having a trunk flexion similar or  
185 superior to that over a level surface. While trunk movement is suspected to contribute to  
186 forward propulsion on a level surface,<sup>30</sup> the reduced propulsion velocity and the turning  
187 tendency over the cross-slope probably limit the benefit of such flexion. Additionally, as  
188 MWUs who rely on their trunk flexion to push the handrim increase their flexion with  
189 fatigue,<sup>31</sup> they would struggle to keep their propulsion direction.

190 For stability, MWUs with motor trunk impairments rely on their latissimus dorsi to provide  
191 postural control.<sup>32-34</sup> They also sit in a kyphotic pose,<sup>35</sup> that leads to a more protracted

192 scapula.<sup>36</sup> When rolling over a cross-slope, the participants leaned laterally which would  
193 induce a transient “scoliotic spine” curvature. This spine configuration decreases scapular  
194 range of motion,<sup>37</sup> and increases latissimus dorsi activation on the convex side (downhill  
195 slope).<sup>38</sup> As the scapula is already protracted, and its range of motion is limited by the induced  
196 spine curvature, the upper limb kinematics during propulsion over a cross-slope would rely  
197 mostly on the glenohumeral joint, disturbing the scapulohumeral rhythm and increasing the  
198 load on scapulohumeral muscles to maintain glenohumeral stability. Additionally, we expect  
199 the latissimus dorsi to particularly develop fatigue much faster over a cross-slope, as it would  
200 be involved in the lateral spine adjustment, the postural stability, the humeral kinematics, as  
201 well as the expiratory function of tetraplegics<sup>39</sup> which also increases over a cross-slope.<sup>5</sup>  
202 Wheelchair propulsion generates superiorly directed joint reaction forces.<sup>40</sup> After the  
203 latissimus dorsi and teres major, the infraspinatus and subscapularis are some of the major  
204 contributors to superior stability<sup>41</sup>, putting them at higher risk of fatigue when over a cross-  
205 slope. On the other hand, compressive forces on the supraspinatus tendon through the humeral  
206 head have already been linked to tendinous injury<sup>42</sup>. Thus, the fatigue of the infraspinatus and  
207 subscapularis would increase the risk of the supraspinatus tendon degradation.

208 As the right latissimus dorsi had a higher activation, for most participants, when on the uphill  
209 side, the force necessary for the wheel braking was probably higher than for other functions.  
210 From a glenohumeral stability point of view, this activation is appreciated as it would help  
211 depress the humerus, reducing the risk of impingement. Indeed, MWUs should be encouraged  
212 to actively retract and depress their scapula when braking the uphill wheel, to reduce the risk  
213 of large glenohumeral joint reaction forces induced by the posterior deltoid activation.

#### 214 *Glenohumeral joint and muscle excitations adaptations*

215 While each participant modified their glenohumeral kinematics differently over the cross-  
216 slope, glenohumeral extension and adduction generally increased and internal rotation

217 increased solely for the downhill side. Little can be found in the literature about the risk of  
218 shoulder pathology at low elevation angles. For propulsion over a level surface, the humeral  
219 head is anteriorly positioned throughout the propulsion cycle, with a low risk of  
220 impingement.<sup>43,44</sup> With the glenohumeral adaptations to the cross-slope, the anterior humeral  
221 position might increase.<sup>45</sup> The compression applied from the humeral head to the biceps long  
222 head and supraspinatus tendon is also likely to increase.<sup>42</sup> This is coherent with the  
223 conclusions of Sakai et al.<sup>46</sup> from MRI observations, relating supraspinatus tears to an upward  
224 axial pressure applied by the humeral head. Additionally, the supraspinatus tendon  
225 architecture allows for fascicles, separated by a lubricant, to move independently.<sup>47</sup> This  
226 property is probably important over the cross-slope due to the increased tendon excursion.<sup>47</sup>  
227 Yet, the larger compression would oppose the lubrication effect, increasing friction and,  
228 consequently, the shear constraint between the fascicles. Such constraint is coherent with the  
229 supraspinatus tears occurring at the intrasubstance or articular regions.<sup>48</sup> Thus, cross-slope  
230 propulsion might increase the anterior glenohumeral head instability and the load on the  
231 supraspinatus tendon.

232 Similar to previous studies that reported no significant differences between level propulsion  
233 and a 2.5% cross-slope for the anterior deltoid, the pectoralis major and the infraspinatus peak  
234 and mean muscle activations<sup>49,50</sup>, most participants of this study had comparable EMG levels  
235 for the leveled and cross-slope propulsions. This lack of difference can be related to the  
236 reduced propulsion velocity. Indeed, as participants were instructed to propel themselves at a  
237 comfortable velocity, adjusting their velocity might have limited the need to increase their  
238 muscle activation. On the other hand, comparing the muscle activation based on the right limb  
239 position over the cross-slope, the anterior and posterior muscle groups tend to increase their  
240 activation on the downhill and uphill side, respectively. This evolution is particularly visible  
241 for the tetraplegic participants. This might highlight the additional burden associated with the

242 limited control of the hand and elbow extensor muscles, as participants try to initiate or brake  
243 the rotation of the wheel. Further studies are needed to understand the interaction between the  
244 handrim contact forces and the shoulder activation patterns.

#### 245 *WSP and recommendations*

246 Participants were heterogeneous in terms of wheelchair skills with WST scores going from  
247 41% up to 89%. This heterogeneity might be related to how they acquired their skills, as they  
248 had various amounts of training. Those with no to little formal training have probably self-  
249 trained to acquire more complex skills. Particularly, for cross-slope propulsion, self-training  
250 might explain why the participants adapted differently to the cross-slope. As some techniques  
251 seemed to be less susceptible to lead to injury and more efficient than others, successfully  
252 crossing the slope seems a far cry from simply passing the skill, highlighting the importance  
253 of a training program. Given the differences between paraplegic and tetraplegic participants,  
254 the training tips for these two groups might differ. Specifically, for those with paraplegia, the  
255 existing training tips found in the WSP should be used to improve biomechanical efficiency  
256 of this skill, even if the MWU has the strength to do it in a less efficient manner. Indeed,  
257 while all paraplegic participants could successfully do a wheelie, none of them opted to propel  
258 their wheelchair in a wheelie position over the cross-slope during the WST, despite this  
259 technique being the only WSP tip that eliminates the wheelchair turning tendency. For those  
260 with tetraplegia, given the additional strain necessary to push or brake the wheel, we  
261 recommend providing education to raise awareness of the importance of trunk and  
262 glenohumeral stability as well as the benefits of cross-slopes avoidance when possible to  
263 minimize their negative impacts. Moreover, our work highlights the need to explore the  
264 impact of positioning devices (e.g., lateral supports) and wheelchair modifications (e.g.,  
265 power assist wheels, handrim projections) on this skill. Such results would help clinicians to

266 weigh the impact of positioning devices and wheelchair modifications on other wheelchair  
267 skills or daily-life activities.

268 As anterior stability is of concern, exercises to help the MWUs identify glenohumeral and  
269 thoracohumeral motions are essential to improve the MWUs proprioception so that they start  
270 relying on their scapulothoracic muscles.<sup>51</sup> Particularly, adducting and depressing the scapula  
271 should help reduce the strain on the glenohumeral joint.

272 When using a wheelie is not an option, care should be taken in choosing the technique to  
273 achieve asymmetry between the downhill and uphill sides. While alternating pushing and  
274 braking on the uphill handrim is probably the worst approach, clinicians should encourage  
275 MWUs to try different ratios of push to brake, or different ratios of uphill to downhill push  
276 frequencies to find the optimal configuration that would least disturb their trunk stability,  
277 account for their strength limitations, and enable trajectory control.

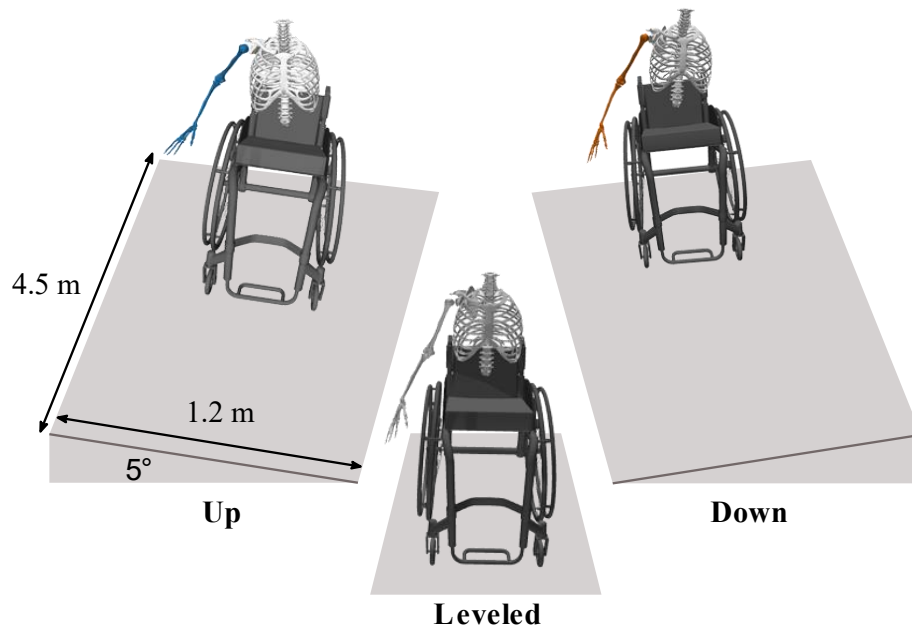
### 278 *Study Limitations*

279 This study has some limitations. First, as the curvature of the trunk had an impact on the  
280 upper limb, and since the adaptations of the trunk probably did not occur at the same spine  
281 level, using more markers to track the spine would have given us better insight into trunk  
282 adaptations. Secondly, EMG data could not be used to compare participants and should be  
283 considered with care. Indeed, some of the muscles were not fully innervated. Thus, a higher  
284 EMG does not necessarily equate with a higher muscle force. Testing muscle groups on an  
285 isometric ergometer should complete the adaptation's understanding, although it would make  
286 for an even longer and more demanding data collection. Our sample of convenience included  
287 nine spinal cord injury patients. Accordingly, our conclusions should be further confirmed  
288 with a bigger sample size. Nevertheless, this study's results would help guide hypothesis-  
289 based future studies to shorten the duration of the data collection, while increasing the number

290 of trials and participants. This study should be replicated for other populations such as  
291 patients with stroke as they typically propel with one arm and one leg. It would also be  
292 interesting to investigate the effect of the cross slope on the other components of the handrim  
293 contact forces. As such study might help further understand the burden associated with cross-  
294 slope propulsion on the tetraplegic population. Finally, while we measured handrim forces  
295 and kinematics for both uphill and downhill sides, our setup was limited to the right limb. It  
296 would be interesting to get a synchronous uphill and downhill analysis using experimental  
297 data from both the left and right limbs.

## 298 **CONCLUSIONS**

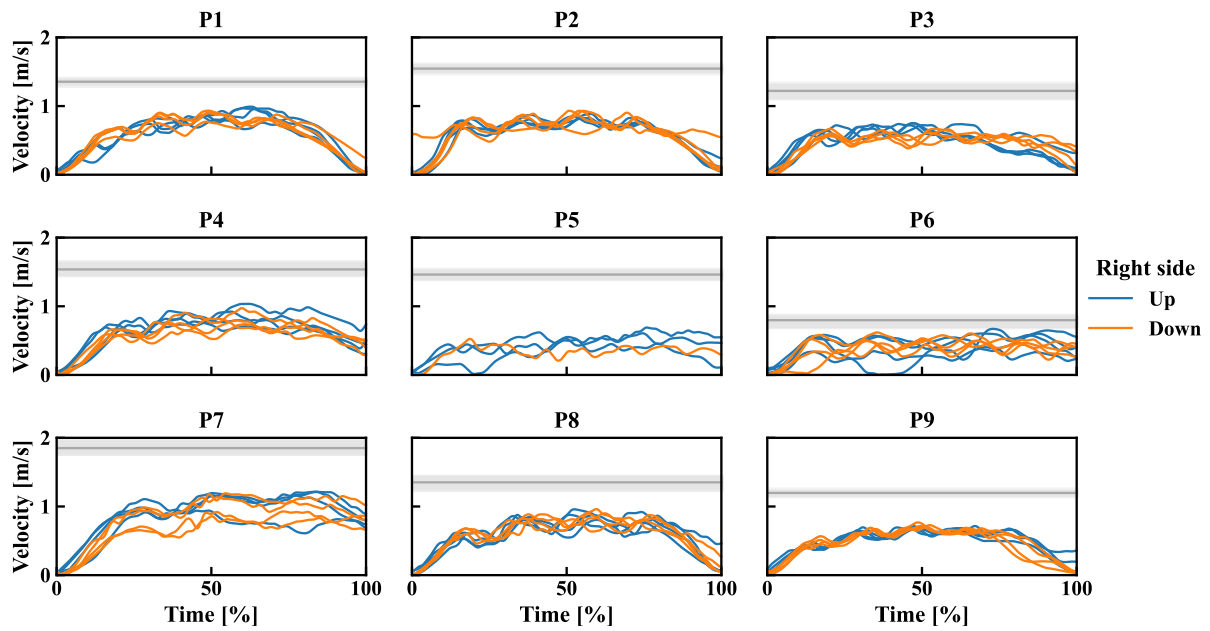
299 Through this exploratory study, we presented a broader analysis of wheelchair propulsion  
300 over a cross-slope, a functional and common task encountered in daily propulsion. The  
301 analysis of this skill was done in light of the current clinical recommendations. Based on the  
302 analysis of the participants' uphill arm technique and trunk kinematics, we suggested potential  
303 injury mechanisms linked to cross-slope propulsion that warrant further investigation and  
304 validation. Our study hinted to the importance of wheelchair skills training programs that  
305 incorporate condition-specific guidance on posture, kinematics, and muscle control as crucial  
306 elements in cultivating a safe and effective technique. Finally, our results should help raise  
307 clinicians' and MWUs' awareness to the importance of exploring wheelchair modifications  
308 and positioning devices to reduce potential for injury.



310

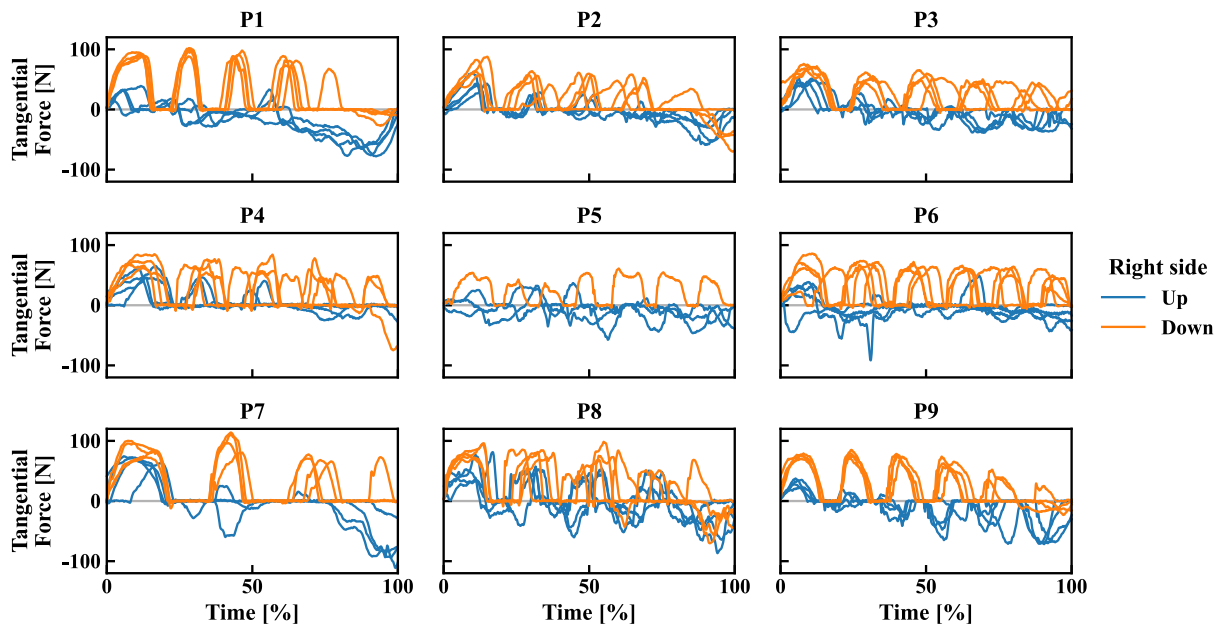
311

Fig. 1. Conditions of the wheelchair propulsion



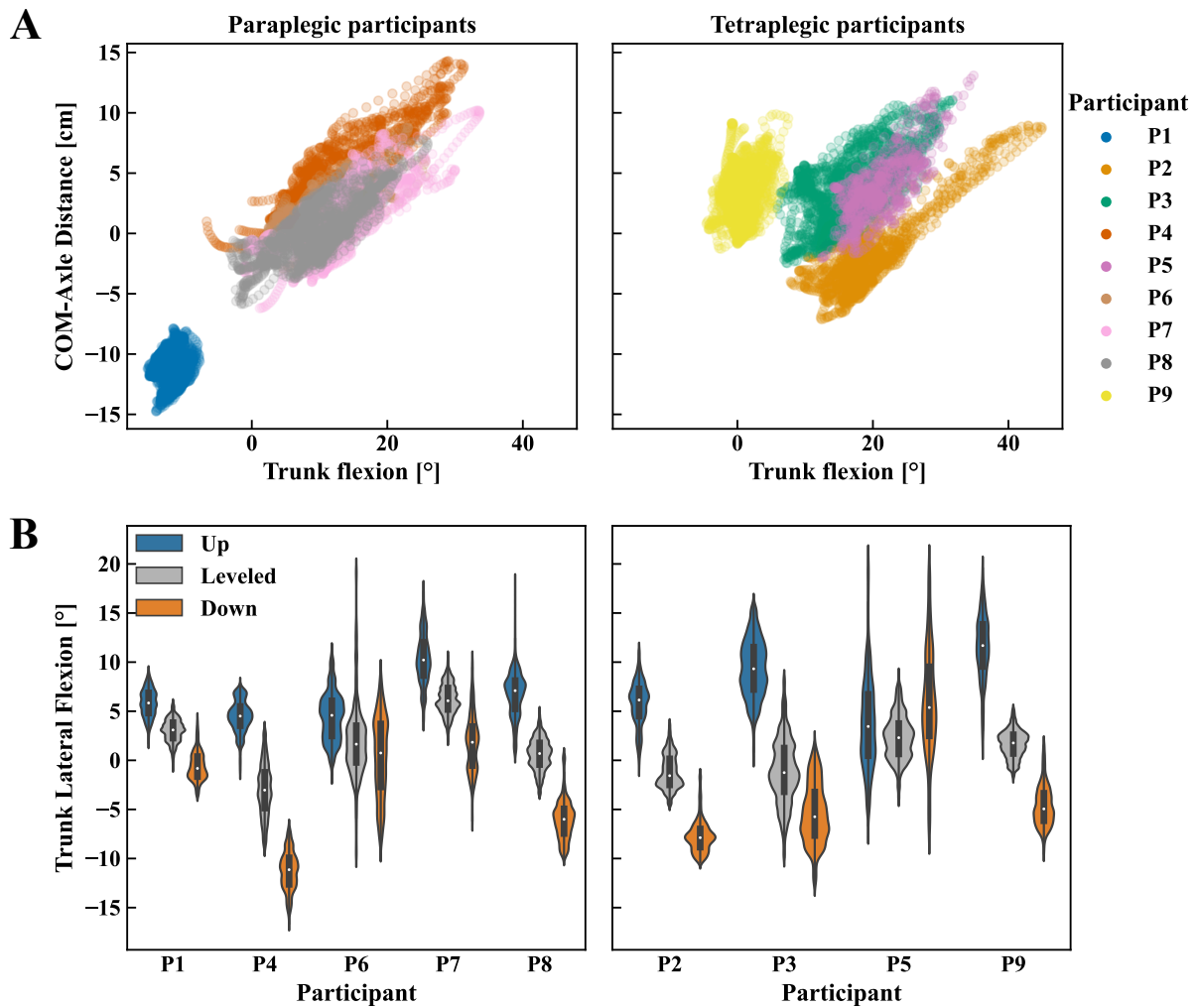
312

313 Fig. 2. Wheelchair velocity for each participant for both conditions: right arm on the uphill (blue) and downhill  
 314 (orange). The grey horizontal line and span within shows the median and interquartile range of the wheelchair  
 315 velocity during level surface propulsion. The time has been normalized with 0% the start of wheelchair motion  
 316 and 100% the stop of the motion, or when the wheelchair rotation was over  $5^\circ$  for participants that turned their  
 317 wheelchair downhill to stop. (For interpretation of the references to color in this figure legend, the reader is  
 318 referred to the web version of this article.)



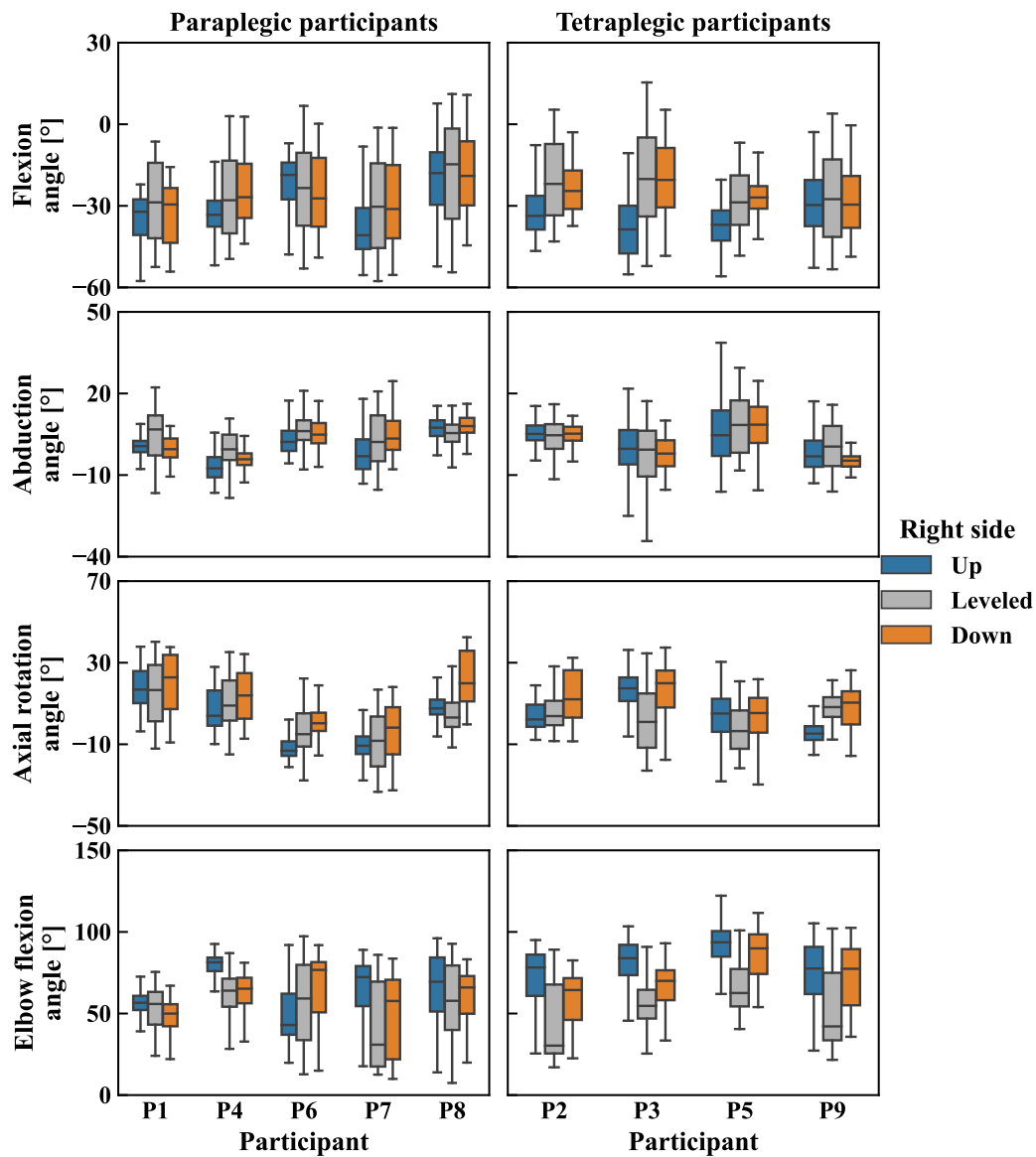
320

321 Fig. 3. Handrim contact tangential force for each participant for both conditions: right arm on the uphill (blue) and  
 322 downhill (orange). The time has been normalized with 0% the start of wheelchair motion and 100% the stop of the  
 323 motion, or when the wheelchair rotation was over  $5^\circ$  for participants that turned their wheelchair downhill to stop.  
 324 (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this  
 325 article.)



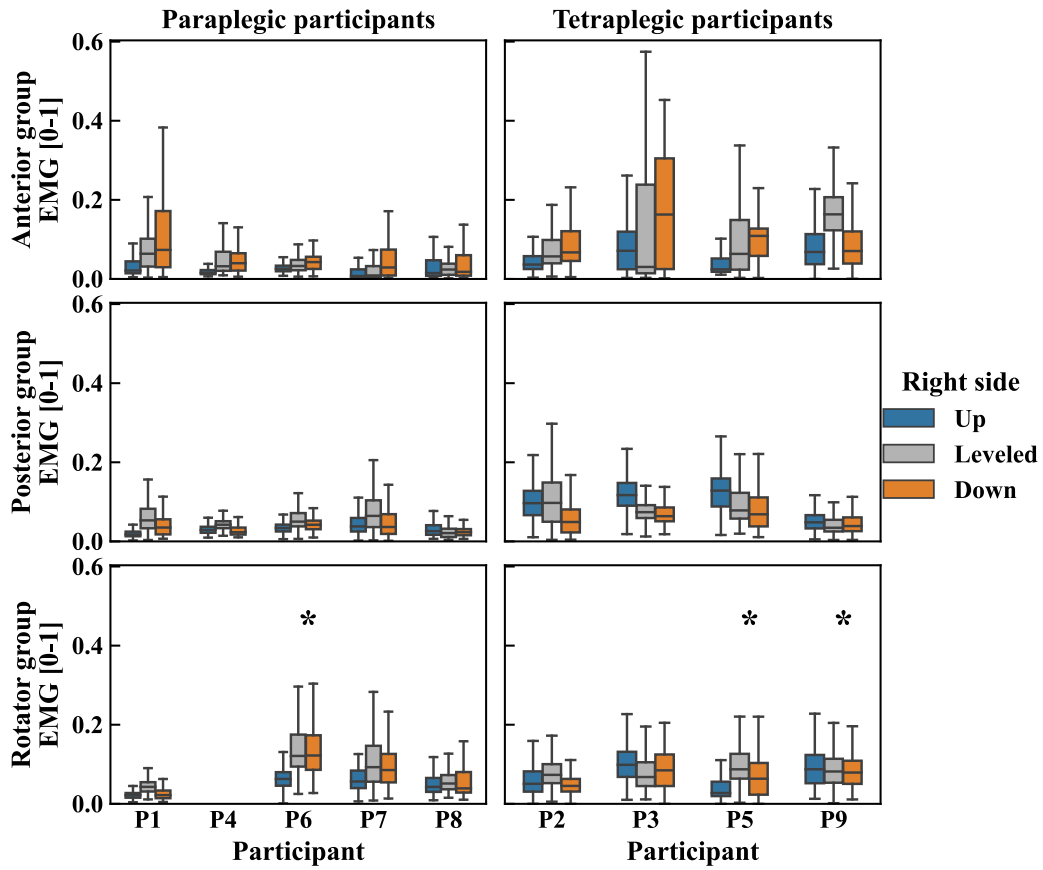
326

327 Fig. 4. Trunk kinematics over a cross-slope: (A) the distance between the rear wheels' axle and the trunk and right  
 328 upper limb center of mass  $d_{COM-axle}$  increases with trunk flexion over a cross-slope (top panel) and the (B)  
 329 distribution of the trunk's lateral flexion over a cross-slope (blue: right limb uphill, orange: right limb downhill)  
 330 and a level surface (grey). Paraplegic and tetraplegic participants are regrouped on the left and right figures,  
 331 respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web  
 332 version of this article.)



333

334 Fig. 5. Glenohumeral and elbow kinematics for the uphill arm (blue) and downhill (orange) over a cross-slope and  
 335 over a leveled surface (grey). The median value is the horizontal line, the boxes represent the interquartile range  
 336 of the data ( $IQR = [Q1, Q3]$ ), and the whiskers display the data within  $[Q1 - 1.5 * IQR, Q3 + 1.5 * IQR]$ . (For  
 337 interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



338

339 Fig. 6. EMG of the different muscle groups for the uphill arm (blue) and downhill (orange) over a cross-slope and  
 340 over a leveled surface (grey). The median value is the horizontal line, the boxes represent the interquartile range  
 341 of the data ( $IQR = [Q1, Q3]$ ), and the whiskers display the data within  $[Q1 - 1.5 * IQR, Q3 + 1.5 * IQR]$ . \* on the  
 342 EMG rotator group points to participants with no subscapularis data, as their scapula was not flexible enough to  
 343 allow access to the muscle. (For interpretation of the references to color in this figure legend, the reader is referred  
 344 to the web version of this article.)

1 Table 1: Participant's position and applied resistance during each MVC.

<b>POSITION</b>	<b>RESISTANCE</b>
Seated with the arm flexed at 90°, elbow extended, and palm facing down.	Resistance to arm flexion at the elbow.
Seated with the arm abducted at 90°, elbow extended, and palm facing down.	Resistance to arm abduction at the elbow.
Prone with the arm horizontally abducted at 90° and the elbow flexed at 90°.	Resistance to horizontal abduction at the elbow
Seated with the arm flexed at 125° and the elbow extended.	Resistance to arm flexion at both the elbow and the inferior angle of the scapula.
Seated with the arm abducted at 30° and the elbow flexed at 90°.	Resistance to arm adduction at the elbow.
Seated with the arm abducted at 90°, the elbow extended, the palm facing down, and the neck bent to the arm side.	Resistance to arm abduction at both the head and the elbow.
Prone with the arm at 90° horizontal abduction, the elbow extended and the thumb pointing to the ceiling.	Resistance to horizontal abduction at the elbow.
Prone with the arm horizontally flexed at 90° in line with the lower trapezius line of action, the elbow extended and the thumb pointing to the ceiling.	Resistance to horizontal flexion at the elbow.
Seated with the arm abducted at 90° and the elbow flexed at 90°.	Resistance to arm adduction at the elbow.
Seated with the arms flexed at 90° and the elbows flexed so that the palms of both hands are in contact.	Pressing hands together.
Lying on the side with the arm at the side, the elbow extended and the palm facing down.	Resistance to arm abduction at the wrist.
Lying on the side with the arm at the side and the elbow at 90° flexion.	Resistance to external rotation at the wrist.
Prone, with the back of the hand in contact with the upper lumbar spine.	Resistance to internal rotation at the wrist.
Seated, the arm at a neutral position and the elbow at 90° flexion with the forearm in supination.	Resistance to elbow flexion at the wrist.
Seated, the arm 90° abducted, the elbow at 90° flexion with the forearm in a neutral.	Resistance to elbow extension at the wrist.

2 Table 2. Demographics and characteristics of the participants P1 to P9

Participant (sex)	Age (years)	Mass (kg)	Months using the MWC	MWC mass (kg)	Injury level	WUSPI [0-150]	WST (%)	WST-CS [0-3]	MWC training
P1 (f)	29	73	48	12.9	T10	19	60.22	2	No training
P2 (m)	34	67	72	13.5	C7	19.28	87.10	3	~ 10 h of training
P3 (m)	28	70	48	22.2	C4-5	40	41.38	2	3-4 h of training
P4 (m)	40	72	12	14.4	T8	15	68.82	2	Two sessions a week for about a year
P5 (m)	24	68	41	16.5	C4-5 (C6-7) *	46.25	50.00	1	No training
P6 (m)	27	65	24	19.1	T3	24.65	75.27	2	Training every day for 3 months
P7 (m)	38	58	18	16.8	T11-12	62.5	88.89	3	Some average training
P8 (m)	29	80	18	15.1	T4	29	80.00	2	No training
P9 (m)	39	89	19	16.9	C6-7	26.25	47.78	2	Few average 15-min training sessions
<b>Mean ± std</b>	32 ± 5.5	71.3 ± 9.1	33.3 ± 18.9	16.4 ± 2.7		33.8 ± 14.3	66.61 ± 16.61		

**Notes: WST-CS is the WST score for the cross-slope skill. Details about the WST and the WUSPI scoring can be found in supplementary material. MWC training reports the answer of the participants when asked about their training during the interview. No training meant no formal training. Abbreviation: f(emale), m(ale), MWC(manual wheelchair)**

**\* The injury level assessment evolved from a C4-5 to C6-7 since the time of injury.**

## 1 REFERENCES

- 2 1. Levasseur M, Desrosiers J, St-Cyr Tribble D. Subjective Quality-of-Life Predictors for  
3 Older Adults with Physical Disabilities. *American Journal of Physical Medicine &*  
4 *Rehabilitation*. 2008;87:830–41.
- 5 2. Smith EM, Sakakibara BM, Miller WC. A review of factors influencing participation in  
6 social and community activities for wheelchair users. *Disability and Rehabilitation:*  
7 *Assistive Technology*. 2016;11:361–74.
- 8 3. Jensen MP, Kuehn CM, Amtmann D, Cardenas DD. Symptom Burden in Persons With  
9 Spinal Cord Injury. *Archives of Physical Medicine and Rehabilitation*. 2007;88:638–45.
- 10 4. Mortenson WB, Miller WC, Backman CL, Oliffe JL. Association Between Mobility,  
11 Participation, and Wheelchair-Related Factors in Long-Term Care Residents Who Use  
12 Wheelchairs as Their Primary Means of Mobility. *Journal of the American Geriatrics*  
13 *Society*. 2012;60:1310–5.
- 14 5. Brubaker CE, McLaurin CA, McClay IS. Effects of side slope on wheelchair  
15 performance. *J Rehabil Res Dev*. 1986;23:55–8.
- 16 6. Cooper RA, Teodorski EE, Sporer ML, Collins DM. Manual Wheelchair Propulsion  
17 Over Cross-Sloped Surfaces: A Literature Review. *Assistive Technology*. 2011;23:42–51.
- 18 7. Rouvier T, Louessard A, Simonetti E, Hybois S, Bascou J, Pontonnier C, et al. Manual  
19 wheelchair biomechanics while overcoming various environmental barriers: A systematic  
20 review. *PLOS ONE*. 2022;17:e0269657.
- 21 8. Richter WM, Rodriguez R, Woods KR, Axelson PW. Consequences of a Cross Slope on  
22 Wheelchair Handrim Biomechanics. *Archives of Physical Medicine and Rehabilitation*.  
23 2007;88:76–80.
- 24 9. Sauret C, Faye V, Bascou J, Pillet H, Lavaste F. Handrim mechanical power during  
25 wheelchair propulsion on level and cross-slope surfaces: a preliminary study. *Computer*  
26 *Methods in Biomechanics and Biomedical Engineering*. 2013;16:124–5.
- 27 10. Mercer JL, Boninger M, Koontz A, Ren D, Dyson-Hudson T, Cooper R. Shoulder joint  
28 kinetics and pathology in manual wheelchair users. *Clin Biomech*. 2006;21:781–9.
- 29 11. Briley SJ, Vegter RJK, Goosey-Tolfrey VL, Mason BS. The longitudinal relationship  
30 between shoulder pain and altered wheelchair propulsion biomechanics of manual  
31 wheelchair users. *Journal of Biomechanics*. 2021;126:110626.
- 32 12. Boninger ML, Dicianno BE, Cooper RA, Towers JD, Koontz AM, Souza AL. Shoulder  
33 magnetic resonance imaging abnormalities, wheelchair propulsion, and gender. *Archives*  
34 *of Physical Medicine and Rehabilitation*. 2003;84:1615–20.
- 35 13. Chénier F, Malbequi J, Gagnon DH. Proposing a new index to quantify instantaneous  
36 symmetry during manual wheelchair propulsion. *Journal of Biomechanics*. 2017;51:137–  
37 41.

- 38 14. Kirby RL, Rush PW, Smith C, Routhier F, Archambault PS, Axelson PW, et al.  
39 Wheelchair Skills Program Manual Version 5.2 [Internet]. Dalhousie University, Halifax,  
40 Nova Scotia, Canada: 2021 [cited 2022 Apr 22]. Available from:  
41 [www.wheelchairskillsprogram.ca/eng/manual.php](http://www.wheelchairskillsprogram.ca/eng/manual.php)
- 42 15. Kirby RL, Rushton P, Smith C, Routhier F. Wheelchair Skills Test Version 5.0. 2018;
- 43 16. Curtis KA, Roach KE, Applegate EB, Amar T, Benbow CS, Genecco TD, et al.  
44 Reliability and validity of the Wheelchair User's Shoulder Pain Index (WUSPI).  
45 *Paraplegia*. 1995;33:595–601.
- 46 17. Neer CS, Welsh RP. The shoulder in sports. *Orthop. Clin. North Am.* 1977;8:583–91.
- 47 18. Hawkins RJ, Kennedy JC. Impingement syndrome in athletes. *Am J Sports Med.*  
48 1980;8:151–8.
- 49 19. Hertel R, Ballmer FT, Lombert SM, Gerber C. Lag signs in the diagnosis of rotator cuff  
50 rupture. *J Shoulder Elbow Surg.* 1996;5:307–13.
- 51 20. Gerber C, Hersche O, Farron A. Isolated rupture of the subscapularis tendon. *J Bone Joint*  
52 *Surg Am.* 1996;78:1015–23.
- 53 21. Dal Maso F, Marion P, Begon M. Optimal Combinations of Isometric Normalization  
54 Tests for the Production of Maximum Voluntary Activation of the Shoulder Muscles.  
55 *Arch. Phys. Med. Rehabil.* 2016;97:1542-1551.e2.
- 56 22. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, et al. OpenSim: Open-  
57 Source Software to Create and Analyze Dynamic Simulations of Movement. *IEEE Trans.*  
58 *Biomed. Eng.* 2007;54:1940–50.
- 59 23. Martinez R, Assila N, Goubault E, Begon M. Sex differences in upper limb  
60 musculoskeletal biomechanics during a lifting task. *Applied Ergonomics.*  
61 2020;86:103106.
- 62 24. Chénier F, Aissaoui R, Gauthier C, Gagnon DH. Wheelchair pushrim kinetics  
63 measurement: A method to cancel inaccuracies due to pushrim weight and wheel camber.  
64 *Medical Engineering & Physics.* 2017;40:75–86.
- 65 25. The pandas development team. pandas-dev/pandas: Pandas 0.24.2 [Internet]. 2020 [cited  
66 2022 Apr 29]; Available from: <https://doi.org/10.5281/zenodo.3509134>
- 67 26. Harris CR, Millman KJ, van der Walt SJ, Gommers R, Virtanen P, Cournapeau D, et al.  
68 Array programming with NumPy. *Nature.* 2020;585:357–62.
- 69 27. Kirshblum SC, Burns SP, Biering-Sorensen F, Donovan W, Graves DE, Jha A, et al.  
70 International standards for neurological classification of spinal cord injury (Revised  
71 2011). *J Spinal Cord Med.* 2011;34:535–46.
- 72 28. Dallmeijer AJ, van der Woude LHV, (DirkJan) Veeger HEJ, Hollander AP. Effectiveness  
73 of force application in manual wheelchair propulsion in persons with spinal cord injuries.  
74 *American Journal of Physical Medicine & Rehabilitation.* 1998;77:213–21.

- 75 29. Astier M, Faupin A, Sauret C, Bascou J. Case study: biomechanical analysis of trunk  
76 stability in two modes of propulsion of manual wheelchair during start and stabilized  
77 speed. *Computer Methods in Biomechanics and Biomedical Engineering*. 2019;22:S175–  
78 6.
- 79 30. van Dijk M, Slikke R van der, Berger M, Hoozemans M, Veeger D. LOOK MUMMY,  
80 NO HANDS! THE EFFECT OF TRUNK MOTION ON FORWARD WHEELCHAIR  
81 PROPULSION [Internet]. In: *ISBS Proceedings Archive*. Canberra Australia: 2021. p.  
82 312. Available from: <https://commons.nmu.edu/isbs/vol39/iss1/80>
- 83 31. Rodgers MM. Influence of trunk flexion on biomechanics of wheelchair propulsion.  
84 2000;13.
- 85 32. Seelen HAM, Potten YJM, Huson A, Spaans F, Reulen JPH. Impaired balance control in  
86 paraplegic subjects. *Journal of Electromyography and Kinesiology*. 1997;7:149–60.
- 87 33. Louis N, Gorce P. Surface electromyography activity of upper limb muscle during  
88 wheelchair propulsion: Influence of wheelchair configuration. *Clinical Biomechanics*.  
89 2010;25:879–85.
- 90 34. Błaszczyszyn M, Borysiuk Z, Piechota K, Kręcisz K, Zmarzły D. Wavelet coherence as a  
91 measure of trunk stabilizer muscle activation in wheelchair fencers. *BMC Sports Science,*  
92 *Medicine and Rehabilitation*. 2021;13:140.
- 93 35. Minkel JL. Seating and Mobility Considerations for People With Spinal Cord Injury.  
94 *Physical Therapy*. 2000;80:701–9.
- 95 36. Moroder P, Akgün D, Plachel F, Baur ADJ, Siegert P. The influence of posture and  
96 scapulothoracic orientation on the choice of humeral component retrotorsion in reverse  
97 total shoulder arthroplasty. *Journal of Shoulder and Elbow Surgery*. 2020;29:1992–2001.
- 98 37. Rapp van Roden AE. The Impact of Trunk Deformity on Shoulder Mechanics and  
99 Implications for Upper Extremity Function after Corrective Spinal Surgery in Idiopathic  
100 Scoliosis [Internet]. 2017 [cited 2022 Apr 13]; Available from:  
101 <https://udspace.udel.edu/handle/19716/23171>
- 102 38. Kwok G, Yip J, Cheung M-C, Yick K-L. Evaluation of Myoelectric Activity of Paraspinal  
103 Muscles in Adolescents with Idiopathic Scoliosis during Habitual Standing and Sitting.  
104 *Biomed Res Int*. 2015;2015:958450.
- 105 39. Fujiwara T, Hara Y, Chino N. EXPIRATORY FUNCTION IN COMPLETE  
106 TETRAPLEGICS: Study of Spirometry, Maximal Expiratory Pressure, and Muscle  
107 Activity of Pectoralis Major and Latissimus Dorsi Muscles: 1. *American Journal of*  
108 *Physical Medicine & Rehabilitation*. 1999;78:464–9.
- 109 40. Chang L-S, Ke X-W, Limroongreungrat W, Wang YT. Relationship Between Shoulder  
110 Pain and Joint Reaction Forces and Muscle Moments During 2 Speeds of Wheelchair  
111 Propulsion. *Journal of Applied Biomechanics*. 2022;38:404–11.
- 112 41. Halder AM, Zhao KD, O’Driscoll SW, Morrey BF, An KN. Dynamic contributions to  
113 superior shoulder stability. *Journal of Orthopaedic Research*. 2001;19:206–12.

- 114 42. Cook JL, Purdam C. Is compressive load a factor in the development of tendinopathy? Br  
115 J Sports Med. 2012;46:163–8.
- 116 43. Mazingo JD, Akbari-Shandiz M, Van Straaten MG, Murthy NS, Schueler BA, Holmes  
117 DR, et al. Comparison of glenohumeral joint kinematics between manual wheelchair tasks  
118 and implications on the subacromial space: A biplane fluoroscopy study. Journal of  
119 Electromyography and Kinesiology. 2022;62:102350.
- 120 44. Mazingo JD, Akbari-Shandiz M, Murthy NS, Van Straaten MG, Schueler BA, Holmes  
121 DR, et al. Shoulder mechanical impingement risk associated with manual wheelchair  
122 tasks in individuals with spinal cord injury. Clinical Biomechanics. 2020;71:221–9.
- 123 45. Dal Maso F, Raison M, Lundberg A, Arndt A, Allard P, Begon M. Glenohumeral  
124 translations during range-of-motion movements, activities of daily living, and sports  
125 activities in healthy participants. Clinical Biomechanics. 2015;30:1002–7.
- 126 46. Sakai M, Mutsuzaki T, Shimizu Y, Okamoto Y, Yatabe K, Muraki I, et al. Characteristic  
127 MRI findings of shoulder, elbow, and wrist joints in wheelchair user. Skeletal Radiol.  
128 2021;50:171–8.
- 129 47. Fallon J, Blevins FT, Vogel K, Trotter J. Functional morphology of the supraspinatus  
130 tendon. Journal of Orthopaedic Research. 2002;20:920–6.
- 131 48. Morrow MMB, Van Straaten MG, Murthy NS, Braman JP, Zanella E, Zhao KD. Detailed  
132 Shoulder MRI Findings in Manual Wheelchair Users with Shoulder Pain. BioMed  
133 Research International. 2014;2014:e769649.
- 134 49. Holloway CS, Symonds A, Suzuki T, Gall A, Smitham P, Taylor S. Linking wheelchair  
135 kinetics to glenohumeral joint demand during everyday accessibility activities. In: 2015  
136 37th Annual International Conference of the IEEE Engineering in Medicine and Biology  
137 Society (EMBC). 2015. p. 2478–81.
- 138 50. Symonds A, Holloway C, Suzuki T, Smitham P, Gall A, Taylor SJ. Identifying key  
139 experience-related differences in over-ground manual wheelchair propulsion  
140 biomechanics. Journal of Rehabilitation and Assistive Technologies Engineering.  
141 2016;3:2055668316678362.
- 142 51. Cools AMJ, Struyf F, De Mey K, Maenhout A, Castelein B, Cagnie B. Rehabilitation of  
143 scapular dyskinesis: from the office worker to the elite overhead athlete. Br J Sports Med.  
144 2014;48:692–7.

145

146 **Trunk and glenohumeral joint adaptations to manual wheelchair propulsion over a**  
147 **cross-slope: an exploratory study**

148 *Appendix A: WST and WUSPI scores*

149 The WST includes multiple skills that are scored individually. Each skill is scored on capacity  
150 from 0 to 3. Briefly, a score of three indicates an advanced pass, a score of 2 indicates that the  
151 participant meets all evaluation criteria, but still has room for improvement. A score of 1 is  
152 given when the subject completes the majority but not all the evaluation criteria of the given  
153 skill. Finally, a score of 0 is given when the participant's execution of the skill is incomplete,  
154 unsafe, or if the participant is unwilling to try. A skill can be evaluated as "Not Possible" if  
155 the wheelchair does not have all parts that would allow for a safe execution, or as "Testing  
156 Error" if the evaluator is incapable of assessing the skill. Finally, the global WST score is  
157 evaluated as a percentage of success in individual skills other than those scored as "Not  
158 Possible" or as "Testing Error". The formula is shown below:

159 
$$WST (\%) = \frac{\sum \text{individual skills scores}}{(n_{\text{skills}} - n_{\text{skills scored "Not possible"}} - n_{\text{skills scored "Testing Error"}}) * 3} * 100$$

160 The WUSPI is a 15-item self-report measure of shoulder pain in wheelchair during functional  
161 daily activities. The activities are grouped under four categories: transfers, wheelchair  
162 mobility, self-care and general activities. For each activity, the participant evaluated their pain  
163 between "no pain" (0) to "worst pain ever" (10). The sum of the individual activities' scores is  
164 the raw WUSPI score. To account for activities that were not applicable for certain  
165 participants, a performance corrected score was obtained by dividing the raw WUSPI score by  
166 the number of applicable activities then multiplying it by 15.

167