



Starting and Stopping Kinetics of a Rear Mounted Power Assist for Manual Wheelchairs

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Abstract:	<p>A rear mounted, powered, drive wheel has been developed to assist with mobility for manual wheelchairs in indoor and outdoor modes. To start the wheel, users must initiate handrim propulsion with sufficient force to trigger the motor. To stop the indoor mode, users must apply a braking force through the handrims exceeding the device's deceleration threshold. The objectives of this study were to compare 1) the minimal forces required to start a wheelchair with and without the wheel, and 2) the distances and forces needed to stop a wheelchair at different speeds (3.5km/hr and 6.0km/hr) with and without the device. We used a crossover study design with 24 able-bodied persons. The main outcome measures were stopping distance, peak braking force, starting force, and maximum velocity with a single push. Participants did not use significantly greater starting or stopping forces (%BW) with the add-on. However, stopping distance was significantly shorter using the add-on when normalized to bodyweight (%BW) ($p=0.04$) at both speeds. Given the decreased stopping distances, the add-on may be a viable option for wheelchair users with limited upper limb strength. To evaluate its applicability for real world use, additional research investigating wheelchair users in their natural environments is needed.</p>

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Starting and Stopping Kinetics of a Rear Mounted Power Assist for Manual Wheelchairs

1 ABSTRACT

2 A rear mounted, powered, drive wheel has been developed to assist with mobility for manual
3 wheelchairs in indoor and outdoor modes. To start the wheel, users must initiate handrim
4 propulsion with sufficient force to trigger the motor. To stop the indoor mode, users must apply a
5 braking force through the handrims exceeding the device's deceleration threshold. The objectives
6 of this study were to compare 1) the ~~minimal~~ minimum forces required to start a wheelchair with and
7 without the wheel, and 2) the distances and forces needed to stop a wheelchair at different speeds
8 (3.5km/hr and 6.0km/hr) with and without the device. We used a crossover study design with 24
9 able-bodied persons. The main outcome measures were starting force (% Body Weight (BW)),
10 maximum velocity with a single push, stopping distance, and peak braking force (%BW).
11 ~~starting force, and maximum velocity with a single push. Participants did not have significantly~~
12 increased starting force or maximum velocity with a single push using the add on. Participants
13 had significantly shorter stopping distance ($P=0.045$) ($\eta^2=0.163$) and reduced peak breaking
14 force ($p=0.02$) ($\eta^2=0.351$) using the add-on. ~~did not use significantly greater starting or stopping~~
15 ~~forces (%BW) with the add-on or have greater maximum velocity.~~ However, stopping distance
16 was significantly shorter using the add-on when normalized to bodyweight (%BW) ($p=0.04$) at
17 both speeds. Given the decreased stopping distances, the add-on may be a viable option for
18 wheelchair users with limited upper limb strength. The next step is to evaluate its applicability

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10 19 ~~and clinical relevance by investigating for and real world clinical relevance by investigating use,~~
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12 20 ~~additional research investigating wheelchair users in their natural environments, is needed.~~

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17 22 INTRODUCTION

18
19 23 Although manual wheelchairs are prescribed to increase mobility and improve
20 24 independence (Cooper et al., 2006), almost half of wheelchair users need assistance (Shields,
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22 25 2004). Furthermore, their use of wheelchairs may lead to upper limb injuries. Common injuries
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24 26 include rotator cuff tendonitis, which may cause negative long term consequences including
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26 27 pain, decreased arm strength, and deconditioning (Cooper et al., 1999; Cooper et al., 2006;
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28 28 Kloosterman et al., 2013). Alternatives ~~have been developed, which such as include~~ pushrim-
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30 29 activated power-assist wheels (PAPAWs), powered wheelchairs, ~~or and~~ scooters (Kloosterman et
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32 30 al., 2013) have been developed, to overcome some of the issues associated with wheelchair use
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34 31 issues.

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36 32 PAPAWs are motorized wheels that are attached to ~~a~~ manual wheelchairs (Kloosterman
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38 33 et al., 2013; Levy et al., 2004). With each push on the handrims, the motors within the wheels
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40 34 engage, allowing the individual to use less effort per push. There has been considerable research
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42 35 on PAPAWs, which has highlighted the potential benefits of ~~these the device devices~~ (Algood et
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44 36 al., 2004; Algood et al., 2005; Arva et al., 2001; Best et al., 2006; Cooper et al., 2001; Corfman

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10 37 et al., 2003; Ding et al., 2008; Fitzgerald et al., 2003, Giesbrecht et al., 2009; Kloosterman et al.,
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12 38 2012; Levy et al., 2010; Lighthall-Haubert et al., 2009; Nash et al., 2008). For example, among
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14 39 those with spinal cord injuries who had shoulder pain, PAPAWs reduced energy costs, perceived
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16 40 exertion, and allowed users to increase distance propelled significantly. However, one
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18 41 disadvantage of PAPAWs is the added weight of the wheels (approximately 26kg/~~59lb~~) (Nash et
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22 42 al., 2008).

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24 43 The SmartDrive™ ([MAX Mobility, 2016](#)) is a relatively new power assist device for
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26 44 manual wheelchairs. As illustrated in Figure 1, [the MX1 model](#) includes two components: a
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28 45 battery, ~~which that~~ is mounted under the seat, and a drive wheel that hooks on to the [camber tube](#)
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32 46 [axle](#) of the wheelchair (Figure 1). To engage the drive wheel, the user needs to exceed a
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34 47 minimum acceleration threshold, at which point the drive wheel will begin to turn. Unlike
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36 48 PAPAWs, the sensors to detect acceleration of the chair are not located in the handrims but in the
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38 49 drive wheel. The drive has two modes: indoor and outdoor. Once activated, the drive will
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41 50 continue to propel the wheelchair at the highest velocity the user has achieved. [This is in contrast](#)
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44 51 [to the PAPAWs, which continue to need hand-rim input in order to continue propelling the](#)
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46
47 52 [individual](#). To stop the wheelchair in the indoor mode, users need to apply sufficient braking
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49 53 force through the hand rims to exceed the device's deceleration threshold, at which point the
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51 54 drive disengages. In contrast, to stop the wheelchair in the outdoor mode, the user needs to push

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10 55 a stop button and hold the hand rims. The outdoor mode is useful, because the drive will cut off
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12 56 in the indoor mode when there are decelerations above a certain threshold (e.g., thresholds, curb
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14 57 cuts, cracks in the sidewalk). The owner's manual indicates it can help propel wheelchairs up to
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16 58 8.85km/hr (~~5.50mph~~) on level ground or 8.0km/hr (~~5.00mph~~) on a 6° incline. The SmartDrive™
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18 59 is lighter than PAPAWS- (approximately 9kg/~~19lb~~), which may make it easier to use (Levy et
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22 60 al., 2004).

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24 61 Although it might be anticipated that a rear mounted power assist would produce similar
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26 62 benefits as PAPAWS, the device's lighter weight and unique design warrants specific attention.
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28 63 Clinically, it has been observed that some wheelchair users cannot start the device, or more
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30 64 problematically, may have difficulty stopping it. Therefore, our study aimed to compare the force
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32 65 required to start and stop a wheelchair with and without the drive at different speeds.
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36 66 Additionally, the stopping distance and peak total force after a single push were measured. Given
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38 67 that force = mass x acceleration, we anticipated either increased force would be required with the
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40 68 device (in light of its added mass) or deceleration would be reduced (and stopping distance
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42 69 would increase). ~~It was hypothesized that it would take a greater total force to start and stop a~~
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44 70 ~~wheelchair with the drive attached.~~
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49 METHODS

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10 72 The study used a cross-over study design, in which participants were evaluated with and
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12 73 without the drive. The local university and hospital ethics board approved the study.
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14 74 **Participants**

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17 75 Able-bodied participants were only included in order to reduce heterogeneity that occurs
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20 76 with using participants with disabilities and to reduce the likelihood of injuries during sudden
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22 77 stops with the device. Twelve~~12~~ male and twelve ~~12~~ female able-bodied individuals were
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24 78 recruited with a mean age of 30.5 ± 12.4 years (mean age ± SD) (See Table 1). Seven of the
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26
27 79 participants had some experience in using a manual wheelchair (i.e. sports day events, family
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29 80 owned wheelchairs). The inclusion criteria for the study was that~~Therefore, to be included in the~~
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31 81 ~~study,~~ participants ~~needed~~had to be over 18 years of age, ambulatory, English speaking, and
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33
34 82 without any upper/lower extremity physical or neurologic problems,~~and English speaking.~~
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37 83 Participants were recruited via posters on bulletin boards and the website at our local hospital
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39 84 and research centre.
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42 85 [Insert Table 1]
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45 86 **Data Collection**

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10 87 After informed consent was obtained, demographic and clinical background information
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12 88 was recorded from each participant. This information included age, height, weight, sex, grip
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14 89 strength, and prior experience using a manual wheelchair.

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17 90 The right rear wheel of a rigid ultralight wheelchair (Tilite TR™) was replaced with a
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19 91 Smart^{WHEEL}. This instrumented wheel uses six strain gauges to measure 3D forces and moments
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22 92 applied to the pushrim. Data from the SmartWheel™ were collected at 240Hz using proprietary
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24 93 software and filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 20 Hz.
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26 94 Variables collected with the SmartWheel™ included three dimensional forces (Newtons), total force
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28 95 ($\sqrt{F_x^2+F_y^2+F_z^2}$), tangential force (force acting on forward propulsion), cadence (cycles/s), push angle
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30 96 (angle (degrees) that the hand was in contact with the pushrim during the propulsion phase), velocity
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32 97 (m/s), and mechanical efficiency (tangential force²/total force²). These data were used ~~Smart^{WHEEL}~~
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34 98 ~~software was used~~ to calculate *peak total force* (% body weight) and *speed* (m/s) and, *stopping*
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39 99 *distance* (meters).

100 Protocol

101 Participants had the opportunity to get familiar with the manual wheelchair before data
102 collection began for approximately 5-10 minutes with and without the drive. Since this part of
103 the study was primarily about stopping, instruction was not provided on specific propulsion

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10 104 techniques. The same wheelchair was used for all participants. Rear tires were inflated to 100 psi
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12 105 prior to testing. The participants were randomized to begin the study either with or without the
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14 106 drive attached to the wheelchair operating in the indoor mode. *Stopping distance* data were
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17 107 collected at two different speeds (3.5 km/hour ~~or 2.2 mph~~ and 6.0 km/h ~~or 3.7 mph~~) with two
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19 108 trials at each speed using a wheelchair treadmill (MaxMobility) at 0.5 degree incline to
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21
22 109 standardize velocities. Participants were instructed to propel on the treadmill until each speed
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24 110 was reached and maintained for a minimum of three seconds. The researcher then asked the
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27 111 participant to stop the wheelchair while simultaneously turning off the treadmill. In a separate
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29 112 test, ~~t~~o measure *starting peak total forces* and *peak speed*, participants were asked to propel the
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32 113 chair with “one light push, in order to get the wheelchair going” from stationary on a level tile
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34 114 floor with and without the drive. Participants were asked to repeat the light push task until they
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37 115 were able to accelerate the chair to engage the drive.

116 **Statistical Analysis**

117 All statistical calculations were performed with SPSS version 22.0 (IBM, Armonk, NY)
118 statistical software and Microsoft Excel (Microsoft, Redmond, WA). A paired t-test was used to
119 analyze the *starting peak total force*, *stopping peak total force*, while repeated measures 2x2
120 ANOVA (RM- ANOVA) was used to compare the *stopping distances*. A p-value of <0.05 was

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10 121 ~~considered significant. Contrasts were used to investigate any interaction effects.~~ Assumptions
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12 122 needed to carry out the RM-ANOVA were verified. Although we allowed participants to
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14 123 practice, the second trial in each data set was used in the analysis to minimize variability due to
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17 124 experience of task. The main effect for speed ~~was and push intensity was~~ not reported since it
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19 125 ~~was they were~~ unrelated to our research questions. Effect sizes were interpreted according to
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21 126 Cohen's guideline (1988). Unless otherwise noted, the interaction effects were not significant
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24 127 between conditions (drive vs. No drive) and the dependent variables (*stopping distance, stopping*
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26
27 128 *peak force, starting peak **total** force, and speed*). All force data were normalised to the body
28
29 129 weight of the participant (% BW).

130 RESULTS

131 ~~As indicated in Table 1, a total of 12 male and 12 female able-bodied individuals were~~
132 ~~recruited with a mean age of 30.5 ± 12.4 years (mean age ± SD). Seven of the participants had~~
133 ~~some experience in using a manual wheelchair (i.e. sports day events, family owned~~
134 ~~wheelchairs).~~

135 ~~{Insert Table 1}~~

136 Stopping (Stopping distance and peak total force)

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10 137 The *stopping distances* at both speeds with and without the drive are reported in Table 2,
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12 138 and the values are represented in Figure 2a. The analysis indicated a *stopping distance*
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14 139 normalized for body weight (%BW) was significantly less ($F=16.0984.79$, $p=0.014$). This is
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16 140 represented in Figure 2b. The *stopping distances* at both 3.5 km/hr (~~2.2 mph~~) and 6.0 km/hr (~~3.7~~
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18 ~~mph~~) were significantly shorter with the drive attached ($F=4.47535$, $p=0.0459$). The normalized
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20 141 stopping distances are represented in Figure 2c. All of the effect sizes are considered large ($\eta^2 >$
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22 142 0.138). The ~~analyses showed no differences in stopping peak total stopping force~~ required for
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24 143 both speeds, was significantly reduced when using the drive ($F=12.4650.45$, $p=0.0254$). This is
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26 144 represented in Ffigure 2c.

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32 146 [Insert Table 2, figure 2]

33 34 35 36 147 **Starting (Peak force and peak velocity)**

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38 148 The ~~peak-starting peak total~~ *force* and *peak speed* are reported in Table 3. Participants
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40 149 did not use a statistically significantly greater force (%BW) with the drive attached ($p=0.24506$),
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42 150 nor was there a significant difference in peak speed at start up between conditions ($p=0.0889$).

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48 49 50 152 **DISCUSSION**

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10 153 This is the first study to investigate the kinetic forces when using a rear mounted powered
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12 154 drive wheel affixed to a manual wheelchair. It is also the first study that the authors are aware of
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14 155 ~~to that studied study~~ stopping forces during wheelchair use rather than typical propulsive forces.
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17 18 156 **Stopping Distance and Peak Force to Stop**

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20 157 Although it was anticipated greater force would be required to stop the device due to the
21
22 158 added weight of the drive, this hypothesis was not supported. Instead, peak stopping force was
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24 159 significantly reduced with the drive. No differences in force between the two conditions were
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26 160 found. This is surprising given the additional mass of ~~Although the SmartDrive™ was ~9kg and~~
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28 161 theoretically should have made stopping more difficult. ~~the additional mass may not have been~~
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30 162 significant enough to produce a difference in force, relative to the mass of the wheelchair and wheelchair
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32 163 user. ~~however, Since~~ participants were able to stop in significantly less distance; ~~however, this~~
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34 164 reduction in stopping force. This may have been due to the inertia and rolling resistance of the
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36 165 drive wheel. Studies have found that solid tires have significantly increased rolling resistance
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38 166 compared solid tires (de Groot et al., 2013) and demonstrate greater increase in rolling resistance
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40 167 with added mass (Kwarciak et al., 2009). comparing the rolling resistance of five different
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42 168 wheels for manual wheelchairs (i.e., three pneumatic (air filled) tires and two solid tires (de
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44 169 Groot et al., 2013)) have shown that the pneumatic tires have significantly reduced rolling
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10 170 ~~resistance compared to the solid tires. Similarly, a study by Kwarciak et al. (2009) showed that~~
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12 171 ~~pneumatic tires exhibited significantly lower rolling resistances and showed smaller increases in~~
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14 172 ~~rolling resistances with added mass (45.4kg/ 100lb, 68.0kg/ 149lb, 90.7kg/ 199lb) compared to~~
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17 173 ~~solid tires. Given that the drive wheel is solid and knobby (given its omni-directional rollers) and~~
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19 174 ~~has a large foot print~~, this could add rolling resistance to the wheelchair, increasing the chair's
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22 175 drag and contributing to the shorter stopping distance with the same amount of force.

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25 176 Although the stopping distance was significantly shorter with the drive, it is unclear
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27 177 whether a decrease in stopping distance of 3 cm (~~1 in.~~) at 3.5 km/h (~~2.2 mph~~) or 5 cm (~~2 in.~~) at 6
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29 178 km/h (~~3.7 mph~~) would be clinically meaningful. ~~That said, this~~ However, ~~t~~ This finding is
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32 179 important as it demonstrates that the device does not increase stopping distances, which would
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35 180 ~~more pose of a~~ potential safety concern. This is particularly important for those individuals who
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37 181 have limited grip strength for braking, such as those with higher-level spinal cord injuries. ~~;~~ In
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39 182 theory, as long as they individuals are able to generate sufficient breaking forces to stop the
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42 183 drive, they ~~can will be able to come to a stop do it~~ in less distance.

184 **Peak Force on First Push and Peak Speed**

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48 185 The peak force on first push was not significantly larger when using the drive and there
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51 186 was no difference in speed on first push. Our value for peak force on first push were similar to

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10 187 ~~those found previously (i.e., -1.23 N/kg (Cowan et al., 2008)). For our values of peak force on first~~
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12 188 ~~pushboth of these variables~~, the p-value ~~trended toward significance~~ ~~did approach significance~~
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14 189 (~~p<.10~~), so a larger sample size may have been required. If larger starting forces are required,
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17 190 the drive could potentially be fatiguing if it is frequently being engaged and disengaged (e.g.
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19 191 manoeuvring in small spaces). The added weight and drag may result in increased work under
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21 192 these circumstances, especially when trying to initiate the drive going up hills or on rougher
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23 193 surfaces. In contrast, for longer distances the drive might require less energy as only steering is
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25 194 required rather than repetitive strokes used for typical manual propulsion.
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30 195 It is difficult to determine whether it is the increased mass or increased drag of the drive
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32 196 is primarily responsible for the study findings. There is conflicting evidence about the effect of
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34 197 adding mass alone to a wheelchair. A study by de Groot et al. (2013) found that extra mass alone
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36 198 added to a manual wheelchair did not have an effect on power output or physical strain;
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38 199 however, their study measured forces during steady-state exercise testing, and they
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40 200 acknowledged there might be differences in physical strain during starting and stopping.
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44 201 Furthermore, in their protocol the extra mass (+5kg/~~11lb~~, +10kg/~~22lb~~) was placed below the
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47 202 seat directly above the rear axis, whereas the added weight of the drive is distributed below the
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49 203 seat (battery pack) and resting on the ground (drive wheel), resulting in some additional drag.
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10 204 | Some studies have shown reduced velocity with increasing weight (7.80-9.05kg) ~~/17.20-20.00kg~~,
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12 205 | without altering changes in normal force on either the front casters or rear wheels) of the
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14 206 | wheelchair (Beekman et al., 1999; Cowan et al., 2009). In contrast, another study found no
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16 207 | significant difference in velocity with increasing weight of the wheelchair (Bednarczyk et al.,
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18 208 | 1994). ~~It may be that the~~ The combination of the additional weight of the device, its distribution
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20 209 | on the chair, ~~as well as and~~ the added rolling resistance of the drive wheel on the ground could
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22 210 | ~~both~~ have contributed to these results.
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28 211 | Methodologically, this is the first study we were able to identify that used a treadmill and
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30 212 | an instrumented wheel to measure stopping forces during wheelchair propulsion. Understanding
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32 213 | how much effort to stop a wheelchair may be just as important as minimising forces and
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34 214 | physiological work during propulsion. This is especially true for determining who might be
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36 215 | suitable to use this kind of power assist drive, as the ability to stop a wheelchair is as important
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38 216 | as the ability to getting it going, particularly for those with limited strength. Thus, creating a
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40 217 | protocol that ensured all participants were wheeling at the same speed prior to stopping was
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42 218 | essential. Our approach using a treadmill is unique to the literature, and can inform future
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44 219 | research in this area.
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50 220 | **Study Limitations**
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10 221 There are two main limitations of the study. First, the measurements of starting forces required
11 222 participants to self-select the force of their pushes. They may have possibly chosen different
12 223 forces for each condition anticipating assistance from the drive. For example, some participants
13 224 were asked to repeat their start trials to engage the device, which may have caused participants to
14 225 push harder during those push trials compared to when the device was not attached. Second,
15 226 although able-bodied participants were chosen to reduce the confounding influence of functional
16 227 difference on the study findings and decrease the potential for injuries with sudden stops on the
17 228 wheelchair treadmill, this ~~does affect~~s the generalizability of the study. An additional limitation
18 229 was that the Smart^{WHEEL} was placed on the right rear wheel, while grip strength was measured
19 230 from the left hand. Future studies could investigate physiological or social impacts of using a
20 231 rear mounted drive wheel with individuals who use wheelchairs for daily indoor and outdoor
21 232 mobility. Including participants who have significantly limited upper extremity strength would
22 233 be beneficial. Further research could also explore the effect of the drive on users' users'
23 234 wheelchair skills and potential usability issues they may encounter (e.g., switching between
24 235 drive modes needing to apply a braking force to turn off the drive (rather than coasting to a stop),
25 236 switching between drive modes). The latter is particularly important as it may be challenging to
26 237 unlearn previous breaking patterns (i.e., needing to switch the drive off before gripping the rims

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10 238 ~~in the outdoor mode). An additional limitation was that the Smart^{WHEEL} was placed on the right~~
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12 239 ~~rear wheel, while grip strength was measured from the left hand.~~
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240 CONCLUSION

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18 241 This study showed that participants were able to reach a complete stop in a shorter distance with
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21 242 ~~less force with the device, although the reduced stopping distance may not be clinically~~
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23 243 ~~meaningful. Although this finding was statistically significant, it may not be clinically~~
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25
26 244 ~~significant. However, Furthermore, P, p~~ participants ~~did not use used~~ more force when initiating
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28 245 movement with the device attached. From a biomechanical perspective, the device may be better
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31 246 for stopping, ~~especially in terms of potential overuse injuries in the upper extremities, but may~~
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33 247 ~~also add stress to upper extremities in conditions where frequent stopping and starting occur.~~
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36 248 ~~However, further research is needed Since the device was designed for longer distances in~~
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38 249 ~~wheelchair users, the next step is to examine the efficacy and utility benefits of the device with~~
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41 250 wheelchair users.

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47
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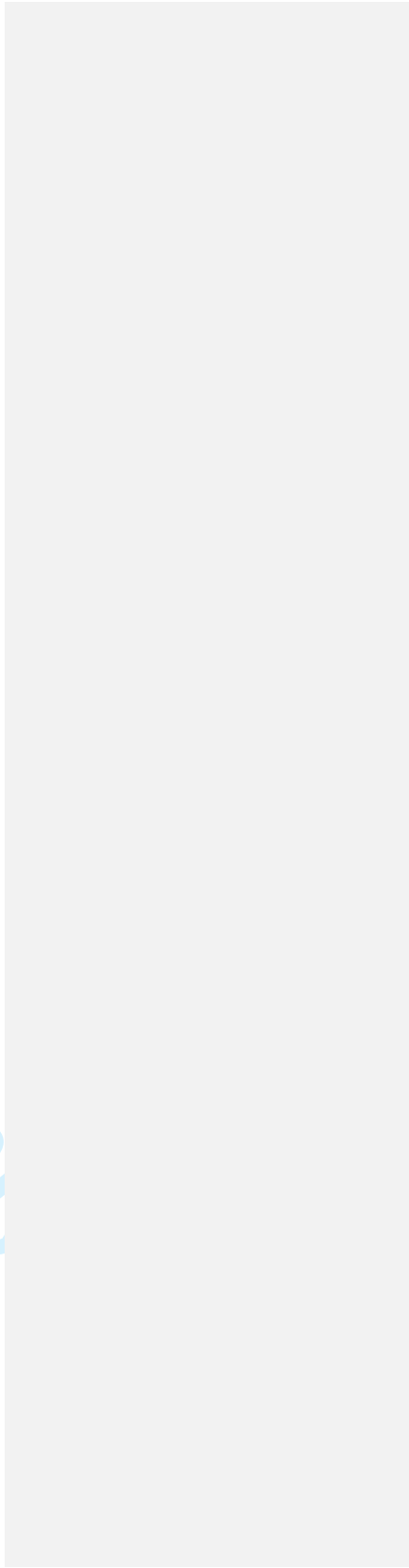
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For Peer Review Only



258 REFERENCES

- 259 ~~1~~-Algood, S. D., Cooper, R.A., Fitzgerald, S.G., Cooper, R., & Boninger, M.L. (2004). Impact
260 of
261 a pushrim-activated power-assisted wheelchair on the metabolic
262 demands, stroke frequency, and range of motion among subjects with tetraplegia.
263 *Archives of Physical Medicine and Rehabilitation*, 85(11), 1865–1871.
- 264 ~~2~~-Algood, S.D., Cooper, R.A., Fitzgerald, S.G., Cooper, R., & Boninger, M.L. (2005). Effect of
265 a pushrim-activated power-assist wheelchair on the functional capabilities of persons
266 with tetraplegia. *Archives of Physical Medicine and Rehabilitation*, 86(3), 380–386.
- 267 ~~3~~-Arva, J., Fitzgerald, S.G., Cooper, R.A., & Boninger, M.L. (2001). Mechanical efficiency and
268 user power requirement with a pushrim activated power assisted wheelchair. *Medical
269 Engineering and Physics*, 23(10), 699–705.
- 270 ~~4~~-Beekman, C.E., Miller-Porter, L., & Schoneberger, M. (1999). Energy cost of propulsion in
271 standard and ultralight wheelchairs in people with spinal cord injuries. *Physical Therapy*,
272 79(2), 146–158.
- 273 ~~5~~-Bednarczyk, J. H., & Sanderson, D.J. (1994). Kinematics of wheelchair propulsion in adults
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10 275 children with spinal cord injury. *Archives of Physical Medicine and Rehabilitation*,
11
12 276 75(12), 1327-1334.

13
14 277 ~~6-~~Best, K.L., Kirby, R.L., Smith, C., & MacLeod, D.A. (2006). Comparison between
15
16 278 performance with a pushrim-activated power-assisted wheelchair and a manual
17
18 279 wheelchair on the Wheelchair Skills Test. *Disability and Rehabilitation*, 28(4), 213-220.

19
20 280 ~~Cooper, R.A., Quatrano, L.A. (1999). Research on Physical Activity and Health among
21
22 281 People with Disabilities: A Consensus Statement. *Journal of Rehabilitation Research and
23
24 282 Development*, 36(2), 142.~~

25
26 283 ~~Cooper, R.A., Fitzgerald, S.G., Boninger, M.L., Prins, K., Rentschler, A.J., Arva, J., et al.
27
28 284 (2001). Evaluation of a pushrim-activated, power-assisted wheelchair. *Archives of
29
30 285 Physical Medicine and Rehabilitation*, 82(5), 702-8.~~

31
32 286 Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd edition). London,
33
34 287 England: Routledge.

35
36 288 ~~7-~~Cooper, R.A., Boninger, M.L., Spaeth, D.M., Ding, D., Guo, S., Koontz, A.M., Fitzgerald, S.
37
38 289 et al.

39
40 290 G., Cooper, R., Kelleher, A., & Collins, D. M. (2006). Engineering better wheelchairs to
41
42 291 enhance community participation. *IEEE Trans Neural Systems and Rehabilitation
43
44 292 Engineering*, 14(4), 438-455.

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8-Cooper, R. A., Fitzgerald, S. G., Boninger, M. L., Prins, K., Rentschler, A. J., Arva, J., &

O'connor, T. J. (2001). Evaluation of a pushrim-activated, power-assisted wheelchair.

Archives of Physical Medicine and Rehabilitation, 82(5), 702–708.

9-Cooper, R. A., Quatrano, L. A., Axelson, P. W., Harlan, W., Stineman, M., Franklin, B.,

Krause,

J. S., Bach, J., Chambers, H., Chao, E. Y., Alexander, M., & Painter, P. (1999). Research

on physical activity and health among people with disabilities: A consensus statement.

Journal of Rehabilitation Research and Development, 36(2), 142-154.

10-Corfman, T.A., Cooper, R.A., Boninger, M.L., Koontz, A.M., & Fitzgerald, S.G. (2003).

Range of motion and stroke frequency differences between manual wheelchair propulsion

and pushrim-activated power-assisted wheelchair propulsion. *Journal of Spinal Cord*

Medicine. 26(2), 135–140.

11-Cotman, C.W., & Berchtold, N.C. (2002). Exercise: A behavioral intervention to enhance

brain

health and plasticity. *Trends in Neuroscience*, 25(6), 295–301.

12-Cowan, R. E., Boninger, M. L., Sawatzky, B. J., Mazoyer, B. D., & Cooper, R. A. (2008).

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10 309 [Preliminary outcomes of the SmartWheel users' group database: A proposed](#)
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12 310 [framework for clinicians to objectively evaluate manual wheelchair](#)
13
14 311 [propulsion](#). *Archives of Physical Medicine and Rehabilitation*, 89(2), 260-268.

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15
16
17 312 ~~13~~ Cowan, R.E., Nash, M.S., Collinger, J.L., Koontz, A.M., & Boninger, M.L. (2009). Impact
18
19 313 on
20
21
22 314 surface type, wheelchair weight, and axle position on wheelchair propulsion by novice
23
24 315 older adults. *Archives of Physical Medicine and Rehabilitation*, 90(7), 1076-1083.

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25
26
27 316 ~~14~~ de Groot, S., Vegter, R.J.K., & van der Woude, L.H.V. (2013). Effects of wheelchair mass,
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29 317 tire type and tire pressure on physical strain and wheelchair propulsion technique.
30
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32 318 *Medical Engineering and Physics*, 35(10), 1476-1482.

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34 319 ~~15~~ Ding, D., Souza, A., Cooper, R.A., Fitzgerald, S.G., Cooper, R., Kelleher, A., & et
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36 320 ~~at~~ Boninger, M.

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39 321 ~~L.~~ (2008). A preliminary study on the impact of pushrim-activated power-assist
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41 322 wheelchairs among individuals with tetraplegia. *American Journal of Physical Medicine*
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43 323 *and Rehabilitation*, 87(10), 821-829.

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46 324 ~~16~~ Fitzgerald, S.G., Arva, J., Cooper, R.A., Dvorznak, M.J., Spaeth, D.M., & Boninger, M.L.
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48 325 (2003). A pilot study on community usage of a pushrim-activated, power-assisted
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50 326 wheelchair. *Assistive Technology*, 15(2), 113-119.

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10 327 ~~17~~-Giesbrecht, E.M., Ripat, J.D., Quanbury, A.O., & Cooper, J.E. (2009). Participation in

11 328 community-based activities of daily living: ~~C~~eomparison of a pushrim-activated, power-

12 329 assisted wheelchair and a power wheelchair. *Disability and Rehabilitation: Assistive*

13 330 *Technology*, 4(3), 198–207.

14
15
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18
19 331 ~~18~~-Kloosterman, M.G.M., Eising, H., Schaake, L., Burke, J.H., & Rietman, J.S. (2012).

20 332 Comparison of shoulder load during power-assisted and purely hand-rim wheelchair

21 333 propulsion. *Clinical Biomechanics*, 27(5), 428–435.

22 334 ~~19~~-Kloosterman, M.G.M., Snoek, G.J., van der Woude, L.H.V., Burke, J.H., & Rietman, J.S.,

23 335 (2013). A systematic review on the pros and cons of using a pushrim-activated power-

24 336 assisted wheelchair. *Clinical Rehabilitation*, 27(4), 299–313.

25 337 ~~20~~-Kwarciak, A.M., Yarossi, M., Ramanujam, A., Dyson-Hudson, T.A., & Sisto, S.A. (2009).

26 338 Evaluation of wheelchair tire rolling resistance using dynamometer-based coast-down

27 339 tests. *Journal of Rehabilitation Research and Development*, 46(7), 931–938.

28 340 ~~Levy, C.E., Chow, J.W. (2004). Pushrim-Activated Power-Assist Wheelchairs: Elegance~~

29 341 ~~in Motion. American Journal of Physical Medicine and Rehabilitation, 83(2), 166–7.~~

30 342 ~~21~~-Levy, C.E., Buman, M.P., Chow, J.W., Tillman, M.D., Fournier, K.A., & Giacobbi, P.

31 343 (2010).

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344 Use of power-assist wheels results in increased distance traveled compared to
 345 conventional manual wheeling. *American Journal of Physical Medicine and*
 346 *Rehabilitation*, 89(8), 625-634.

347 ~~22~~-Levy, C. E., & Chow, J. W. (2004). Pushrim-activated power-assist wheelchairs: Elegance in
 348 motion. *American Journal of Physical Medicine and Rehabilitation*, 83(2), 166-167.

349 ~~23~~-Lighthall-Haubert, L., Requejo, P.S., Mulroy, S.J., Newsam, C.J., Bontrager, E., Gronley, J.

350 K., & Perry, J. et al. (2009). Comparison of shoulder muscle electromyographic activity

351 during standard manual wheelchair and push-rim activated power assisted wheelchair

352 propulsion in persons with complete tetraplegia. *Archives of Physical Medicine and*

353 *Rehabilitation*, 90(11), 1904-1915.

354 MAX Mobility. (2016). *SmartDrive powered by MAX Mobility*. Retrieved from

355 <http://www.max-mobility.com/smartdrive/#mx2>

356 ~~24~~-Nash, M.S., Koppens, D., Haaren, M., Sherman, A.L., Lippiatt, J.P., & Lewis, J.E. (2008).

357 Power-assisted wheels ease energy costs and perceptual response to wheelchair

358 propulsion in persons with shoulder pain and spinal cord injury. *Archives of Physical*

359 *Medicine and Rehabilitation*, 89(11), 2080-2085.

360 ~~25~~-Shields, M. (2004). Use of wheelchairs and other mobility support devices. *Health Reports*,

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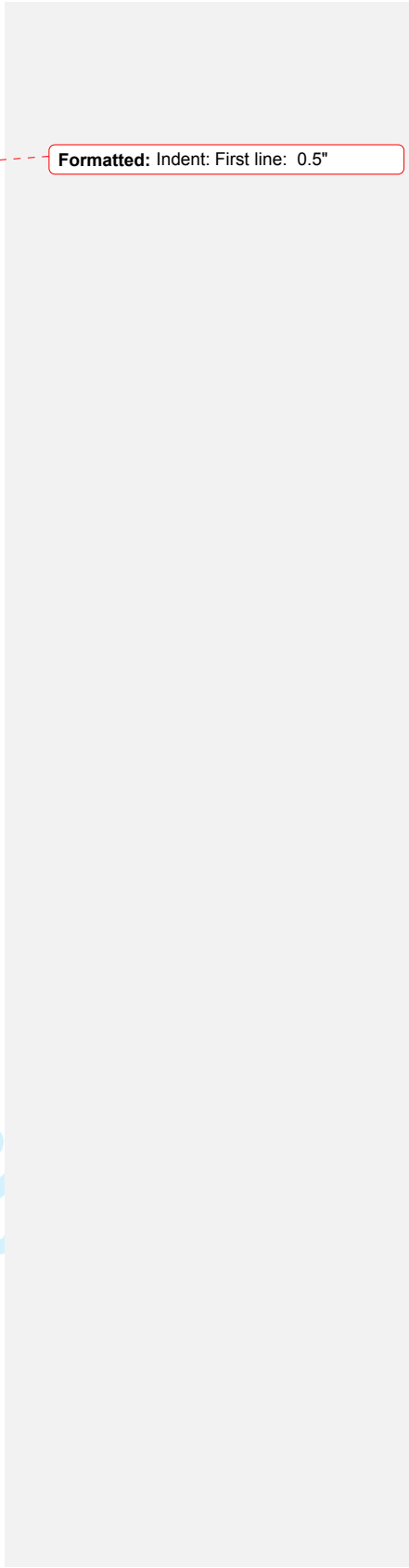
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Starting and Stopping Kinetics of a Rear Mounted Power Assist for Manual Wheelchairs

1 ABSTRACT

2 A rear mounted, powered, drive wheel has been developed to assist with mobility for manual
3 wheelchairs in indoor and outdoor modes. To start the wheel, users must initiate handrim
4 propulsion with sufficient force to trigger the motor. To stop the indoor mode, users must apply a
5 braking force through the handrims exceeding the device's deceleration threshold. The objectives
6 of this study were to compare 1) the minimum force required to start a wheelchair with and
7 without the wheel, and 2) the distances and forces needed to stop a wheelchair at different speeds
8 (3.5km/hr and 6.0km/hr) with and without the device. We used a crossover study design with 24
9 able-bodied persons. The main outcome measures were starting force (% Body Weight (BW)),
10 maximum velocity with a single push, stopping distance, and peak braking force (%BW).
11 Participants did not have significantly increased starting force or maximum velocity with a single
12 push using the add on. Participants had significantly shorter stopping distance ($P=0.045$) (η^2
13 $=0.163$) and reduced peak braking force ($p=0.02$) ($\eta^2 =0.351$) using the add-on. However,
14 stopping distance was significantly shorter using the add-on when normalized to bodyweight
15 (%BW) ($p=0.04$) at both speeds. Given the decreased stopping distances, the add-on may be a
16 viable option for wheelchair users with limited upper limb strength. The next step is to evaluate
17 its applicability and clinical relevance by investigating wheelchair users in their natural
18 environments.

19 INTRODUCTION

20 Although manual wheelchairs are prescribed to increase mobility and improve
21 independence (Cooper et al., 2006), almost half of wheelchair users need assistance (Shields,
22 2004). Furthermore, their use of wheelchairs may lead to upper limb injuries. Common injuries
23 include rotator cuff tendonitis, which may cause negative long term consequences including
24 pain, decreased arm strength, and deconditioning (Cooper et al., 1999; Cooper et al., 2006;
25 Kloosterman et al., 2013). Alternatives such as pushrim-activated power-assist wheels
26 (PAPAWs), powered wheelchairs, and scooters (Kloosterman et al., 2013) have been developed
27 to overcome some of the issues associated with wheelchair use.

28 PAPAWs are motorized wheels that are attached to manual wheelchairs (Kloosterman et
29 al., 2013; Levy et al., 2004). With each push on the handrims, the motors within the wheels
30 engage, allowing the individual to use less effort per push. There has been considerable research
31 on PAPAWs, which has highlighted the potential benefits of the device (Algood et al., 2004;
32 Algood et al., 2005; Arva et al., 2001; Best et al., 2006; Cooper et al., 2001; Corfman et al.,
33 2003; Ding et al., 2008; Fitzgerald et al., 2003, Giesbrecht et al., 2009; Kloosterman et al., 2012;
34 Levy et al., 2010; Lighthall-Haubert et al., 2009; Nash et al., 2008). For example, among those
35 with spinal cord injuries who had shoulder pain, PAPAWs reduced energy costs, perceived
36 exertion, and allowed users to increase distance propelled significantly. However, one

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4 37 disadvantage of PAPAWs is the added weight of the wheels (approximately 26kg) (Nash et al.,
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7 38 2008).
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10 The SmartDrive™ (MAX Mobility, 2016) is a relatively new power assist device for
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14 40 manual wheelchairs. As illustrated in Figure 1, the MX1 model includes two components: a
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17 41 battery that is mounted under the seat, and a drive wheel that hooks on to the camber tube of the
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20 42 wheelchair (Figure 1). To engage the drive wheel, the user needs to exceed a minimum
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23 43 acceleration threshold, at which point the drive wheel will begin to turn. Unlike PAPAWs, the
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26 44 sensors to detect acceleration of the chair are not located in the handrims but in the drive wheel.
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29 45 The drive has two modes: indoor and outdoor. Once activated, the drive will continue to propel
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32 46 the wheelchair at the highest velocity the user has achieved. This is in contrast to the PAPAWs,
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35 47 which continue to need hand-rim input in order to continue propelling the individual. To stop the
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38 48 wheelchair in the indoor mode, users need to apply sufficient braking force through the hand
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41 49 rims to exceed the device's deceleration threshold, at which point the drive disengages. In
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44 50 contrast, to stop the wheelchair in the outdoor mode, the user needs to push a stop button and
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47 51 hold the hand rims. The outdoor mode is useful, because the drive will cut off in the indoor mode
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49
50 52 when there are decelerations above a certain threshold (e.g., thresholds, curb cuts, cracks in the
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53 53 sidewalk). The owner's manual indicates it can help propel wheelchairs up to 8.85km/hr on level
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4 54 ground or 8.0km/hr on a 6° incline. The SmartDrive™ is lighter than PAPAWs (approximately
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7 55 9kg), which may make it easier to use (Levy et al., 2004).
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10 56 Although it might be anticipated that a rear mounted power assist would produce similar
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13 57 benefits as PAPAWs, the device's lighter weight and unique design warrants specific attention.
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16 58 Clinically, it has been observed that some wheelchair users cannot start the device, or more
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19 59 problematically, may have difficulty stopping it. Therefore, our study aimed to compare the force
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22 60 required to start and stop a wheelchair with and without the drive at different speeds.
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26 61 Additionally, the stopping distance and peak total force after a single push were measured. Given
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29 62 that force = mass x acceleration, we anticipated either increased force would be required with the
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32 63 device (in light of its added mass) or deceleration would be reduced (and stopping distance
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35 64 would increase).
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38 65 **METHODS**

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41 66 The study used a cross-over study design, in which participants were evaluated with and
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44 67 without the drive. The local university and hospital ethics board approved the study.
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47 68 **Participants**

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50 69 Able-bodied participants were only included in order to reduce heterogeneity that occurs
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53 70 with using participants with disabilities and to reduce the likelihood of injuries during sudden
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56 71 stops with the device. Twelve male and twelve female able-bodied individuals were recruited
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4 72 with a mean age of 30.5 ± 12.4 years (mean age \pm SD) (See Table 1). Seven of the participants
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7 73 had some experience in using a manual wheelchair (i.e. sports day events, family owned
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10 74 wheelchairs). The inclusion criteria for the study was that participants had to be over 18 years of
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13 75 age, ambulatory, English speaking, and without any upper/lower extremity physical or
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16 76 neurologic problems. Participants were recruited via posters on bulletin boards and the website at
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19 77 our local hospital and research centre.
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24 78 [Insert Table 1]
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27 79 **Data Collection**

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31 80 After informed consent was obtained, demographic and clinical background information
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34 81 was recorded from each participant. This information included age, height, weight, sex, grip
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37 82 strength, and prior experience using a manual wheelchair.
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41 83 The right rear wheel of a rigid ultralight wheelchair (Tilite TR™) was replaced with a
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43 84 Smart^{WHEEL}. This instrumented wheel uses six strain gauges to measure 3D forces and moments
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46 85 applied to the pushrim. Data from the SmartWheel™ were collected at 240Hz using proprietary
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49 86 software and filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 20 Hz.
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52 87 Variables collected with the SmartWheel™ included three dimensional forces (Newtons), total force
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55 88 ($\sqrt{F_x^2+F_y^2+F_z^2}$), tangential force (force acting on forward propulsion), cadence (cycles/s), push angle
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4 89 (angle (degrees) that the hand was in contact with the pushrim during the propulsion phase), velocity
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7 90 (m/s), and mechanical efficiency ($\text{tangential force}^2/\text{total force}^2$). These data were used to calculate
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10 91 *peak total force* (% body weight) and *speed* (m/s) and, *stopping distance* (meters).
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13 14 92 **Protocol**

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18 93 Participants had the opportunity to get familiar with the manual wheelchair before data
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21 94 collection began for approximately 5-10 minutes with and without the drive. Since this part of
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24 95 the study was primarily about stopping, instruction was not provided on specific propulsion
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27 96 techniques. The same wheelchair was used for all participants. Rear tires were inflated to 100 psi
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29
30 97 prior to testing. The participants were randomized to begin the study either with or without the
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33 98 drive attached to the wheelchair operating in the indoor mode. *Stopping distance* data were
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36 99 collected at two different speeds (3.5 km/hour and 6.0 km/h) with two trials at each speed using a
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39 100 wheelchair treadmill (MaxMobility) at 0.5 degree incline to standardize velocities. Participants
40
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42 101 were instructed to propel on the treadmill until each speed was reached and maintained for a
43
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45 102 minimum of three seconds. The researcher then asked the participant to stop the wheelchair
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48 103 while simultaneously turning off the treadmill. In a separate test, to measure *starting peak total*
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51 104 *forces* and *peak speed*, participants were asked to propel the chair with “one light push, in order
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54 105 to get the wheelchair going” from stationary on a level tile floor with and without the drive.
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4 106 Participants were asked to repeat the light push task until they were able to accelerate the chair to
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7 107 engage the drive.
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10 11 **Statistical Analysis**

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15 109 All statistical calculations were performed with SPSS version 22.0 (IBM, Armonk, NY)
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18 110 statistical software and Microsoft Excel (Microsoft, Redmond, WA). A paired t-test was used to
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21 111 analyze the *starting peak total force*, *stopping peak total force*, while repeated measures 2x2
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24 112 ANOVA (RM- ANOVA) was used to compare the *stopping distances*. A p-value of <0.05 was
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27 113 considered significant. Assumptions needed to carry out the RM-ANOVA were verified.
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30 114 Although we allowed participants to practice, the second trial in each data set was used in the
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33 115 analysis to minimize variability due to experience of task. The main effect for speed was not
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36 116 reported since it was unrelated to our research questions. Effect sizes were interpreted according
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39 117 to Cohen's guideline (1988). Unless otherwise noted, the interaction effects were not significant
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41
42 118 between conditions (drive vs. No drive) and the dependent variables (*stopping distance*, *stopping*
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45 119 *peak force*, *starting peak total force*, and *speed*). All force data were normalised to the body
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48 120 weight of the participant (% BW).
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51 52 53 **RESULTS**

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4 122 **Stopping (Stopping distance and peak total force)**
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8 123 The *stopping distances* at both speeds with and without the drive are reported in Table 2,
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11 124 and the values are represented in Figure 2a. The analysis indicated a *stopping distance*
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14 125 normalized for body weight (%BW) was significantly less ($F=16.098$, $p=0.01$). This is
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17 126 represented in Figure 2b. The *stopping distances* at both 3.5 km/hr and 6.0 km/hr were
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20 127 significantly shorter with the drive attached ($F=4.475$, $p=0.045$). The normalized stopping
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23 128 distances are represented in Figure 2c. All of the effect sizes are considered large ($\eta^2 > 0.138$).
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26 129 The *peak total stopping force* required for both speeds, was significantly reduced when using the
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29 130 drive ($F=12.465$, $p=0.02$). This is represented in Figure 2c.
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34 131 [Insert Table 2, figure 2]
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38 132 **Starting (Peak force and peak velocity)**
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41 133 The *starting peak total force* and *peak speed* are reported in Table 3. Participants did not
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44 134 use a statistically significantly greater force (%BW) with the drive attached ($p=0.245$), nor was
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47 135 there a significant difference in peak speed at start up between conditions ($p=0.088$).
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52 136 [Insert Table 3]
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56 137 **DISCUSSION**
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4 138 This is the first study to investigate the kinetic forces when using a rear mounted powered
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7 139 drive wheel affixed to a manual wheelchair. It is also the first study that the authors are aware of
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10 140 that studied stopping forces during wheelchair use rather than typical propulsive forces.
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14 141 **Stopping Distance and Peak Force to Stop**

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17 142 Although it was anticipated greater force would be required to stop the device due to the
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20 143 added weight of the drive, this hypothesis was not supported. Instead, peak stopping force was
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23 144 significantly reduced with the drive. . This is surprising given the additional mass of the
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26 145 SmartDrive™ was ~9kg and theoretically should have made stopping more difficult. . h Since
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29 146 participants were able to stop in significantly less distance; however, this reduction in stopping
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32 147 force may have been due to the inertia and rolling resistance of the drive wheel. Studies have
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35 148 found that solid tires have significantly increased rolling resistance compared solid tires (de
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38 149 Groot et al., 2013) and demonstrate greater increase in rolling resistance with added mass
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41 150 (Kwarciak et al., 2009). . Given that the drive wheel is solid and knobby (given its omni-
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44 151 directional rollers) and has a large foot print, this could add rolling resistance to the wheelchair,
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47 152 increasing the chair's drag and contributing to the shorter stopping distance with the same
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50 153 amount of force.
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4 154 Although the stopping distance was significantly shorter with the drive, it is unclear
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7 155 whether a decrease in stopping distance of 3 cm at 3.5 km/h or 5 cm at 6 km/h would be
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10 156 clinically meaningful. However, this finding is important as it demonstrates that the device does
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13 157 not increase stopping distances, which would pose a potential safety concern. This is particularly
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16 158 important for those individuals who have limited grip strength for braking, such as those with
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19 159 higher-level spinal cord injuries. In theory, as long as individuals are able to generate sufficient
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22 160 breaking forces to stop the drive, they will be able to come to a stop in less distance.
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26 161 **Peak Force on First Push and Peak Speed**

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30 162 The peak force on first push was not significantly larger when using the drive and there
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33 163 was no difference in speed on first push. Our value for peak force on first push were similar to
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36 164 those found previously (i.e., 1.23 N/kg (Cowan et al., 2008)). For our values of peak force on first
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39 165 push, the p-value trended toward significance, so a larger sample size may have been required.
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42 166 If larger starting forces are required, the drive could potentially be fatiguing if it is frequently
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45 167 being engaged and disengaged (e.g. manoeuvring in small spaces). The added weight and drag
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48 168 may result in increased work under these circumstances, especially when trying to initiate the
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51 169 drive going up hills or on rougher surfaces. In contrast, for longer distances the drive might
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4 170 require less energy as only steering is required rather than repetitive strokes used for typical
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7 171 manual propulsion.
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11 172 It is difficult to determine whether it is the increased mass or increased drag of the drive
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14 173 is primarily responsible for the study findings. There is conflicting evidence about the effect of
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17 174 adding mass alone to a wheelchair. A study by de Groot et al. (2013) found that extra mass alone
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20 175 added to a manual wheelchair did not have an effect on power output or physical strain;
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23 176 however, their study measured forces during steady-state exercise testing, and they
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26 177 acknowledged there might be differences in physical strain during starting and stopping.
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29 178 Furthermore, in their protocol the extra mass (+5kg, +10kg) was placed below the seat directly
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32 179 above the rear axis, whereas the added weight of the drive is distributed below the seat (battery
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35 180 pack) and resting on the ground (drive wheel), resulting in some additional drag. Some studies
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38 181 have shown reduced velocity with increasing weight (7.80-9.05kg), without altering changes in
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41 182 normal force on either the front casters or rear wheels) of the wheelchair (Beekman et al., 1999;
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44 183 Cowan et al., 2009). In contrast, another study found no significant difference in velocity with
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47 184 increasing weight of the wheelchair (Bednarczyk et al., 1994). The combination of the additional
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50 185 weight of the device, its distribution on the chair, and the added rolling resistance of the drive
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53 186 wheel on the ground could have contributed to these results.
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4 187 Methodologically, this is the first study we were able to identify that used a treadmill and
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8 188 an instrumented wheel to measure stopping forces during wheelchair propulsion. Understanding
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11 189 how much effort to stop a wheelchair may be just as important as minimising forces and
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14 190 physiological work during propulsion. This is especially true for determining who might be
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17 191 suitable to use this kind of power assist drive, as the ability to stop a wheelchair is as important
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20 192 as the ability to getting it going, particularly for those with limited strength. Thus, creating a
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23 193 protocol that ensured all participants were wheeling at the same speed prior to stopping was
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26 194 essential. Our approach using a treadmill is unique to the literature, and can inform future
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29 195 research in this area.

33 196 **Study Limitations**

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37 197 There are two main limitations of the study. First, the measurements of starting forces required
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40 198 participants to self-select the force of their pushes. They may have possibly chosen different
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43 199 forces for each condition anticipating assistance from the drive. For example, some participants
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46 200 were asked to repeat their start trials to engage the device, which may have caused participants to
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49 201 push harder during those push trials compared to when the device was not attached. Second,
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52 202 although able-bodied participants were chosen to reduce the confounding influence of functional
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55 203 difference on the study findings and decrease the potential for injuries with sudden stops on the
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4 204 wheelchair treadmill, this affects the generalizability of the study. An additional limitation was
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7 205 that the Smart^{WHEEL} was placed on the right rear wheel, while grip strength was measured from
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10 206 the left hand. Future studies could investigate physiological or social impacts of using a rear
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13 207 mounted drive wheel with individuals who use wheelchairs for daily indoor and outdoor
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16 208 mobility. Including participants who have significantly limited upper extremity strength would
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19 209 be beneficial. Further research could also explore the effect of the drive on users' wheelchairs
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22 210 skills and potential usability issues they may encounter (e.g., needing to apply a braking force to
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25 211 turn off the drive (rather than coasting to a stop), switching between drive modes). The latter is
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28 212 particularly important as it may be challenging to unlearn previous breaking patterns (i.e.,
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31 213 needing to switch the drive off before gripping the rims in the outdoor mode).

32 214 **CONCLUSION**

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40 215 This study showed that participants were able to reach a complete stop in a shorter distance with
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43 216 less force with the device, although the reduced stopping distance may not be clinically
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46 217 meaningful. Furthermore, Participants did not use more force when initiating movement with the
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49 218 device attached. From a biomechanical perspective, the device may be better for stopping,
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52 219 especially in terms of potential overuse injuries in the upper extremities. However, further
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55 220 research is needed to examine the efficacy and utility of the device with wheelchair users.
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223 **REFERENCES**

- 224 Algood, S. D., Cooper, R.A., Fitzgerald, S.G., Cooper, R., & Boninger, M. L. (2004). Impact of
225 a pushrim-activated power-assisted wheelchair on the metabolic demands, stroke
226 frequency, and range of motion among subjects with tetraplegia. *Archives of Physical
227 Medicine and Rehabilitation*, 85(11), 1865–1871.
- 228 Algood, S. D., Cooper, R.A., Fitzgerald, S.G., Cooper, R., & Boninger, M.L. (2005). Effect of
229 a pushrim-activated power-assist wheelchair on the functional capabilities of persons
230 with tetraplegia. *Archives of Physical Medicine and Rehabilitation*, 86(3), 380–386.
- 231 Arva, J., Fitzgerald, S.G., Cooper, R.A., & Boninger, M.L. (2001). Mechanical efficiency and
232 user power requirement with a pushrim activated power assisted wheelchair. *Medical
233 Engineering and Physics*, 23(10), 699–705.
- 234 Beekman, C.E., Miller-Porter, L., & Schoneberger, M. (1999). Energy cost of propulsion in
235 standard and ultralight wheelchairs in people with spinal cord injuries. *Physical Therapy*,
236 79(2), 146–158.
- 237 Bednarczyk, J. H., & Sanderson, D.J. (1994). Kinematics of wheelchair propulsion in adults and
238 children with spinal cord injury. *Archives of Physical Medicine and Rehabilitation*,
239 75(12), 1327–1334.
- 240 Best, K.L., Kirby, R.L., Smith, C., & MacLeod, D.A. (2006). Comparison between

- 1
2
3
4 241 performance with a pushrim-activated power-assisted wheelchair and a manual
5
6
7 242 wheelchair on the Wheelchair Skills Test. *Disability and Rehabilitation*, 28(4), 213-220.
8
9
10 243 Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd edition). London,
11
12
13 244 England: Routledge.
14
15
16 245 Cooper, R.A., Boninger, M.L., Spaeth, D.M., Ding, D., Guo, S., Koontz, A.M., Fitzgerald, S.
17
18
19 246 G., Cooper, R., Kelleher, A., & Collins, D. M. (2006). Engineering better wheelchairs to
20
21
22 247 enhance community participation. *IEEE Trans Neural Systems and Rehabilitation*
23
24
25 248 *Engineering*, 14(4), 438–455.
26
27
28
29 249 Cooper, R. A., Fitzgerald, S. G., Boninger, M. L., Prins, K., Rentschler, A. J., Arva, J., &
30
31
32 250 O’connor, T. J. (2001). Evaluation of a pushrim-activated, power-assisted wheelchair.
33
34
35 251 *Archives of Physical Medicine and Rehabilitation*, 82(5), 702–708.
36
37
38 252 Cooper, R. A., Quatrano, L. A., Axelson, P. W., Harlan, W., Stineman, M., Franklin, B., Krause,
39
40
41 253 J. S., Bach, J., Chambers, H., Chao, E. Y., Alexander, M., & Painter, P. (1999). Research
42
43
44 254 on physical activity and health among people with disabilities: A consensus statement.
45
46
47 255 *Journal of Rehabilitation Research and Development*, 36(2), 142-154.
48
49
50 256 Corfman, T.A., Cooper, R.A., Boninger, M.L., Koontz, A.M., & Fitzgerald, S.G. (2003).
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4 257 Range of motion and stroke frequency differences between manual wheelchair propulsion
5
6
7 258 and pushrim-activated power-assisted wheelchair propulsion. *Journal of Spinal Cord*
8
9
10 259 *Medicine*. 26(2), 135–140.
- 11
12
13 260 Cotman, C.W., & Berchtold, N.C. (2002). Exercise: A behavioral intervention to enhance brain
14
15
16 261 health and plasticity. *Trends in Neuroscience*, 25(6), 295–301.
- 17
18
19 262 Cowan, R. E., Boninger, M. L., Sawatzky, B. J., Mazoyer, B. D., & Cooper, R. A. (2008).
20
21
22 263 Preliminary outcomes of the SmartWheel users' group database: A proposed framework
23
24
25 264 for clinicians to objectively evaluate manual wheelchair propulsion. *Archives of Physical*
26
27
28 265 *Medicine and Rehabilitation*, 89(2), 260-268.
- 29
30
31 266 Cowan, R.E., Nash, M.S., Collinger, J.L., Koontz, A.M., & Boninger, M.L. (2009). Impact on
32
33
34 267 surface type, wheelchair weight, and axle position on wheelchair propulsion by novice
35
36
37 268 older adults. *Archives of Physical Medicine and Rehabilitation*, 90(7), 1076-1083.
- 38
39
40 269 de Groot, S., Vegter, R.J.K., & van der Woude, L.H.V. (2013). Effects of wheelchair mass,
41
42
43 270 tire type and tire pressure on physical strain and wheelchair propulsion technique.
44
45
46 271 *Medical Engineering and Physics*, 35(10), 1476-1482.
- 47
48
49 272 Ding, D., Souza, A., Cooper, R.A., Fitzgerald, S.G., Cooper, R., Kelleher, A., & Boninger, M.
50
51
52
53
54
55
56
57
58
59
60

- 1
2
3
4 273 L. (2008). A preliminary study on the impact of pushrim-activated power-assist
5
6
7 274 wheelchairs among individuals with tetraplegia. *American Journal of Physical Medicine*
8
9
10 275 *and Rehabilitation*, 87(10), 821–829.
11
12
13 276 Fitzgerald, S.G., Arva, J., Cooper, R.A., Dvorznak, M.J., Spaeth, D.M., & Boninger, M.L.
14
15
16 277 (2003). A pilot study on community usage of a pushrim-activated, power-assisted
17
18
19 278 wheelchair. *Assistive Technology*, 15(2), 113–119.
20
21
22 279 Giesbrecht, E.M., Ripat, J.D., Quanbury, A.O., & Cooper, J.E. (2009). Participation in
23
24
25 280 community-based activities of daily living: Comparison of a pushrim-activated, power-
26
27
28 281 assisted wheelchair and a power wheelchair. *Disability and Rehabilitation: Assistive*
29
30
31 282 *Technology*, 4(3), 198–207.
32
33
34 283 Kloosterman, M.G.M., Eising, H., Schaake, L., Buurke, J.H., & Rietman, J.S. (2012).
35
36
37 284 Comparison of shoulder load during power-assisted and purely hand-rim wheelchair
38
39
40 285 propulsion. *Clinical Biomechanics*, 27(5), 428–435.
41
42
43 286 Kloosterman, M.G.M., Snoek, G.J., van der Woude, L.H.V., Buurke, J.H., & Rietman, J.S.,
44
45
46 287 (2013). A systematic review on the pros and cons of using a pushrim-activated power-
47
48
49 288 assisted wheelchair. *Clinical Rehabilitation*, 27(4), 299–313.
50
51
52 289 Kwarciak, A.M., Yarossi, M., Ramanujam, A., Dyson-Hudson, T.A., & Sisto, S.A. (2009).
53
54
55
56
57
58
59
60

- 1
2
3
4 290 Evaluation of wheelchair tire rolling resistance using dynamometer-based coast-down
5
6
7 291 tests. *Journal of Rehabilitation Research and Development*, 46(7), 931-938.
8
9
10 292 Levy, C.E., Buman, M.P., Chow, J.W., Tillman, M.D., Fournier, K.A., & Giacobbi, P. (2010).
11
12 293 Use of power-assist wheels results in increased distance traveled compared to
13
14 294 conventional manual wheeling. *American Journal of Physical Medicine and*
15
16 295 *Rehabilitation*, 89(8), 625-634.
17
18
19
20 296 Levy, C. E., & Chow, J. W. (2004). Pushrim-activated power-assist wheelchairs: Elegance in
21
22 297 motion. *American Journal of Physical Medicine and Rehabilitation*, 83(2), 166–167.
23
24
25
26 298 Lighthall-Haubert, L., Requejo, P.S., Mulroy, S.J., Newsam, C.J., Bontrager, E., Gronley, J.
27
28 299 K., & Perry, J. (2009). Comparison of shoulder muscle electromyographic activity during
29
30 300 standard manual wheelchair and push-rim activated power assisted wheelchair propulsion
31
32 301 in persons with complete tetraplegia. *Archives of Physical Medicine and Rehabilitation*,
33
34 302 90(11), 1904–1915.
35
36
37
38 303 MAX Mobility. (2016). *SmartDrive powered by MAX Mobility*. Retrieved from
39
40 304 <http://www.max-mobility.com/smartdrive/#mx2>
41
42
43
44
45
46
47
48
49
50 305 Nash, M.S., Koppens, D., Haaren, M., Sherman, A.L., Lippiatt, J.P., & Lewis, J.E. (2008).
51
52
53
54
55
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57
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306 Power-assisted wheels ease energy costs and perceptual response to wheelchair
307 propulsion in persons with shoulder pain and spinal cord injury. *Archives of Physical
308 Medicine and Rehabilitation*, 89(11), 2080-2085.
309 Shields, M. (2004). Use of wheelchairs and other mobility support devices. *Health Reports*,
310 15(3), 37-41.
311

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Starting and Stopping Kinetics of a Rear Mounted Power Assist for Manual Wheelchairs



Figure 1. SmartDrive power assist.

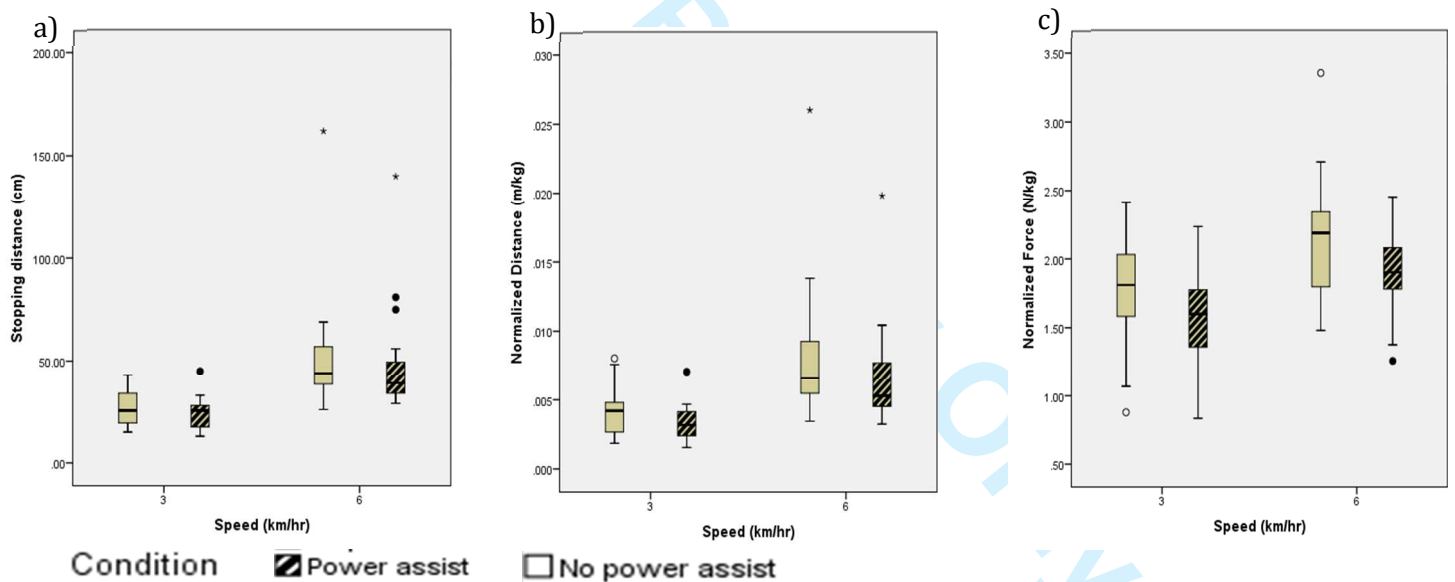


Figure 2. Box plots displaying stopping distances and peak forces at different speeds with and without the SmartDrive power assist (n=24). a) Stopping distance (cm) vs. speed (km/hour). b) Normalized stopping distance (m/kg) vs. speed (km/hour). c) Normalized peak stopping force (N/kg) vs. speed (km/hour).

Table 1. Demographics

Characteristics	Men	Women	All	Range
Age (y)	32.8 ± 13.7	28.2 ± 11.0	30.5 ± 12.4	19-64
Weight (kg)	74.5 ± 8.1	58.5 ± 6.7	66.5 ± 10.9	50-92
Height (m)	175.9 ± 5.4	163.5 ± 4.1	1.7 ± 0.1	1.6-1.9
Average left hand grip strength (kg)	42.9 ± 8.9	27.7 ± 5.9	35.3 ± 10.7	19.7-63.3

Table 2. Stopping Distance and Peak Total Force

	No power assist		power assist		Significance of condition	Effect size (Partial η^2)
	3.5km/hr	6km/hr	3.5km/hr	6km/hr		
Stopping Dist. (cm)	27.0±8.72	50.8±26.4	24.0±7.59	46.5±24.0	p=0.045	0.163
Stopping Dist. (m/kg) · 10 ⁻³ (%BW)	4.239±1.793	8.019±4.694	3.308±1.264	6.347±3.450	p=0.01	0.412
Peak Total Force (N/kg) (%BW)	1.747 ± 0.379	2.097 ± 0.415	1.5492±0.313	1.920±0.287	p=0.02	0.351

Table 3. Minimal starting Forces and Peak Speed

	No power assist	power assist	Significance of condition
Peak total Force (N/kg)	1.258 ± 0.215	1.310 ± 0.220	p=0.088
Peak velocity (m/s)	0.74 ± 0.14	0.69 ± 0.12	p=0.245