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

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Abstract:	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.

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

ABSTRACT

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 minimum~~al~~ force~~s~~ 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 starting force (% Body Weight (BW)), maximum velocity with a single push, stopping distance, and peak braking force (%BW).~~–,~~ ~~starting force, and maximum velocity with a single push.~~ Participants did not have significantly increased starting force or maximum velocity with a single push using the add on. Participants had significantly shorter stopping distance (P=0.045) (η^2 =0.163) and reduced peak breaking force (p=0.02) (η^2 =0.351) using the add-on. ~~did not use significantly greater starting or stopping forces (%BW) with the add-on or have greater maximum velocity.~~ 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. The next step is t~~T~~o evaluate its applicability

and clinical relevance by investigating ~~for and real worldclinical relevance by investigating use, additional research investigating~~ wheelchair users in their natural environments.~~ is needed.~~

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INTRODUCTION

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

PAPAWs are motorized wheels that are attached to ~~a~~ manual wheelchairs (Kloosterman et al., 2013; Levy et al., 2004). With each push on the handrims, the motors within the wheels engage, allowing the individual to use less effort per push. There has been considerable research on PAPAWs, which has highlighted the potential benefits of ~~these~~ the device ~~devices~~ (Algood et al., 2004; Algood et al., 2005; Arva et al., 2001; Best et al., 2006; Cooper et al., 2001; Corfman et al., 2003; Ding et al., 2008; Fitzgerald et al., 2003, Giesbrecht et al., 2009; Kloosterman et al., 2012; Levy et al., 2010; Lighthall-Haubert et al., 2009; Nash et al., 2008). For example, among those with spinal cord injuries who had shoulder pain, PAPAWs reduced energy costs, perceived exertion, and allowed users to increase distance propelled significantly. However, one disadvantage of PAPAWs is the added weight of the wheels (approximately 26kg~~/ 59lb~~) (Nash et al., 2008).

The SmartDrive™ (MAX Mobility, 2016) is a relatively new power assist device for manual wheelchairs. As illustrated in Figure 1, the MX1 model~~it~~ includes two components: a battery~~, which~~ that is mounted under the seat, and a drive wheel that hooks on to the camber tube ~~axle~~ of the wheelchair (Figure 1). To engage the drive wheel, the user needs to exceed a minimum acceleration threshold, at which point the drive wheel will begin to turn. Unlike PAPAWs, the sensors to detect acceleration of the chair are not located in the handrims but in the drive wheel. The drive has two modes: indoor and outdoor. Once activated, the drive will continue to propel the wheelchair at the highest velocity the user has achieved. This is in contrast to the PAPAWs, which continue to need hand-rim input in order to continue propelling the individual. To stop the wheelchair in the indoor mode, users need to apply sufficient braking force through the hand rims to exceed the device's deceleration threshold, at which point the drive disengages. In contrast, to stop the wheelchair in the outdoor mode, the user needs to push a stop button and hold the hand rims. The outdoor mode is useful, because the drive will cut off in the indoor mode when there are decelerations above a certain threshold (e.g., thresholds, curb cuts, cracks in the sidewalk). The owner's manual indicates it can help propel wheelchairs up to 8.85km/hr ~~(5.50mph)~~ on level ground or 8.0km/hr ~~(5.00mph)~~ on a 6^{o} incline. The SmartDrive™ is lighter than PAPAWs~~-~~ (approximately 9kg~~/ 19lb~~), which may make it easier to use (Levy et al., 2004).

Although it might be anticipated that a rear mounted power assist would produce similar benefits as PAPAWs, the device's lighter weight and unique design warrants specific attention. Clinically, it has been observed that some wheelchair users cannot start the device, or more problematically, may have difficulty stopping it. Therefore, our study aimed to compare the force required to start and stop a wheelchair with and without the drive at different speeds. Additionally, the stopping distance and peak total force after a single push were measured. Given that force = mass x acceleration, we anticipated either increased force would be required with the device (in light of its added mass) or deceleration would be reduced (and stopping distance would increase).~~It was hypothesized that it would take a greater total force to start and stop a wheelchair with the drive attached.~~

METHODS

The study used a cross-over study design, in which participants were evaluated with and without the drive. The local university and hospital ethics board approved the study.

Participants

Able-bodied participants were only included in order to reduce heterogeneity that occurs with using participants with disabilities and to reduce the likelihood of injuries during sudden stops with the device. Twelve~~12~~ male and twelve ~~12~~ female able-bodied individuals were recruited with a mean age of 30.5 ± 12.4 years (mean age ± SD) (See Table 1). Seven of the participants had some experience in using a manual wheelchair (i.e. sports day events, family owned wheelchairs). The inclusion criteria for the study was that~~Therefore, to be included in the study,~~ participants ~~needed~~ had to be over 18 years of age, ambulatory, English speaking, and without any upper/lower extremity physical or neurologic problems~~, and English speaking~~. Participants were recruited via posters on bulletin boards and the website at our local hospital and research centre.

[Insert Table 1]

Data Collection

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

The right rear wheel of a rigid ultralight wheelchair (Tilite TR™) was replaced with a Smart$^{\text{WHEEL}}$. This instrumented wheel uses six strain gauges to measure 3D forces and moments applied to the pushrim. Data from the SmartWheel™ were collected at 240Hz using proprietary software and filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 20 Hz. Variables collected with the SmartWheel™ included three dimensional forces (Newtons), total force ($\sqrt{(Fx^2+Fy^2+Fz^2)}$), tangential force (force acting on forward propulsion), cadence (cycles/s), push angle (angle (degrees) that the hand was in contact with the pushrim during the propulsion phase), velocity (m/s), and mechanical efficiency (tangential force^2/total force^2). These data were used ~~Smart$^{\text{WHEEL}}$ software was used~~ to calculate~~d~~ *peak total force* (% body weight) and *speed* (m/s) and, *stopping distance* (meters).

Protocol

Participants had the opportunity to get familiar with the manual wheelchair before data collection began for approximately 5-10 minutes with and without the drive. Since this part of the study was primarily about stopping, instruction was not provided on specific propulsion techniques. The same wheelchair was used for all participants. Rear tires were inflated to 100 psi prior to testing. The participants were randomized to begin the study either with or without the drive attached to the wheelchair operating in the indoor mode. *Stopping distance* data were collected at two different speeds (3.5 km/hour ~~or 2.2 mph~~ and 6.0 km/h ~~or 3.7 mph~~) with two trials at each speed using a wheelchair treadmill (MaxMobility) at 0.5 degree incline to standardize velocities. Participants were instructed to propel on the treadmill until each speed was reached and maintained for a minimum of three seconds. The researcher then asked the participant to stop the wheelchair while simultaneously turning off the treadmill. In a separate test, t~~T~~o measure *starting peak total forces* and *peak speed*, participants were asked to propel the chair with "one light push, in order to get the wheelchair going" from stationary on a level tile floor with and without the drive. Participants were asked to repeat the light push task until they were able to accelerate the chair to engage the drive.

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Statistical Analysis

All statistical calculations were performed with SPSS version 22.0 (IBM, Armonk, NY) statistical software and Microsoft Excel (Microsoft, Redmond, WA). A paired t-test was used to analyze the *starting peak total force*, stopping *peak total force,* while repeated measures 2x2 ANOVA (RM- ANOVA) was used to compare the *stopping distances.* A p-value of <0.05 was considered significant. ~~Contrasts were used to investigate any interaction effects.~~ Assumptions needed to carry out the RM-ANOVA were verified. Although we allowed participants to practice, the second trial in each data set was used in the analysis to minimize variability due to experience of task. The main effect for speed was ~~and push intensity was~~ not reported since it was ~~they were~~ unrelated to our research questions. Effect sizes were interpreted according to Cohen's guideline (1988). Unless otherwise noted, the interaction effects were not significant between conditions (drive vs. No drive) and the dependent variables (*stopping distance, stopping peak force, starting peak total force, and speed*). All force data were normalised to the body weight of the participant (% BW).

RESULTS

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

~~[Insert Table 1]~~

Stopping (Stopping distance and peak total force)

The *stopping distances* at both speeds with and without the drive are reported in Table 2, and the values are represented in Figure 2a. The analysis indicated a *stopping distance* normalized for body weight (%BW) was significantly less (F=16.098~~4.79~~, p=0.014). This is represented in Figure 2b. The *stopping distances* at both 3.5 km/hr ~~(2.2 mph)~~ and 6.0 km/hr ~~(3.7 mph)~~ were significantly shorter with the drive attached (F=4.475~~35~~, p=0.045~~9~~). The normalized stopping distances are represented in Figure 2c. All of the effect sizes are considered large ($\eta^2 > 0.138$) . The ~~analyses showed no differences in *stopping*~~ *peak total stopping force* required for both speeds, was significantly reduced when using the drive (F=12.465~~0.45~~, p=0.02~~51~~). This is represented in F~~f~~igure 2c.

[Insert Table 2, figure 2]

Starting (Peak force and peak velocity)

The ~~*peak*~~ *starting peak total force* and *peak speed* are reported in Table 3. Participants did not use a statistically significantly greater force (%BW) with the drive attached (p=0.245~~06~~), nor was there a significant difference in peak speed at start up between conditions (p=0.088~~9~~).

[Insert Table 3]

DISCUSSION

This is the first study to investigate the kinetic forces when using a rear mounted powered drive wheel affixed to a manual wheelchair. It is also the first study that the authors are aware of ~~to~~ that studied ~~study~~ stopping forces during wheelchair use rather than typical propulsive forces.

Stopping Distance and Peak Force to Stop

Although it was anticipated greater force would be required to stop the device due to the added weight of the drive, this hypothesis was not supported. Instead, peak stopping force was significantly reduced with the drive. ~~No differences in force between the two conditions were found~~. This is surprising given the additional mass of ~~Although~~ the SmartDrive™ was ~9kg and theoretically should have made stopping more difficult. ~~, the additional mass may not have been significant enough to produce a difference in force, relative to the mass of the wheelchair and wheelchair user~~. ~~;~~ h~~owever,~~ Since participants were able to stop in significantly less distance; however, this reduction in stopping force~~. This~~ may have been due to the inertia and rolling resistance of the drive wheel. Studies have found that solid tires have significantly increased rolling resistance compared solid tires (de Groot et al., 2013) and demonstrate greater increase in rolling resistance with added mass (Kwarciak et al., 2009). ~~comparing the rolling resistance of five different wheels for manual wheelchairs (i.e., three pneumatic (air filled) tires and two solid tires (de Groot et al., 2013)) have shown that the pneumatic tires have significantly reduced rolling~~

~~resistance compared to the solid tires. Similarly, a study by Kwarciak et al. (2009) showed that pneumatic tires exhibited significantly lower rolling resistances and showed smaller increases in rolling resistances with added mass (45.4kg/ 100lb, 68.0kg/ 149lb, 90.7kg/ 199lb) compared to solid tires~~. Given that the drive wheel is solid and knobby (given its omni-directional rollers) and has a large foot print, this could add rolling resistance to the wheelchair, increasing the chair's drag and contributing to the shorter stopping distance with the same amount of force.

Although the stopping distance was significantly shorter with the drive, it is unclear 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 km/h ~~(3.7 mph)~~ would be clinically meaningful. ~~That said, this~~However, t~~T~~his finding is important as it demonstrates that the device does not increase stopping distances, which would ~~more~~ pose ~~of~~ a~~a~~ potential safety concern. This is particularly important for those individuals who have limited grip strength for braking, such as those with higher-level spinal cord injuries. ~~;~~ In theory, as long as ~~they~~ individuals are able to generate sufficient breaking forces to stop the drive, they ~~can~~ will be able to come to a stop ~~do it~~ in less distance.

Peak Force on First Push and Peak Speed

The peak force on first push was not significantly larger when using the drive and there was no difference in speed on first push. Our value for peak force on first push were similar to those found previously (i.e.,-1.23 N/kg (Cowan et al., 2008).-For our values of peak force on first push~~both of these variables~~, the p-value trended toward significance ~~did approach significance (p<.10)~~, so a larger sample size may have been required. If larger starting forces are required, the drive could potentially be fatiguing if it is frequently being engaged and disengaged (e.g. manoeuvring in small spaces). The added weight and drag may result in increased work under these circumstances, especially when trying to initiate the drive going up hills or on rougher surfaces. In contrast, for longer distances the drive might require less energy as only steering is required rather than repetitive strokes used for typical manual propulsion.

It is difficult to determine whether it is the increased mass or increased drag of the drive is primarily responsible for the study findings. There is conflicting evidence about the effect of adding mass alone to a wheelchair. A study by de Groot et al. (2013) found that extra mass alone added to a manual wheelchair did not have an effect on power output or physical strain; however, their study measured forces during steady-state exercise testing, and they acknowledged there might be differences in physical strain during starting and stopping. Furthermore, in their protocol the extra mass (+5kg~~/ 11lb~~, +10kg~~/ 22lb~~) was placed below the seat directly above the rear axis, whereas the added weight of the drive is distributed below the seat (battery pack) and resting on the ground (drive wheel), resulting in some additional drag.

Some studies have shown reduced velocity with increasing weight (7.80-9.05kg)~~/ 17.20-20.00lb~~, without altering changes in normal force on either the front casters or rear wheels) of the wheelchair (Beekman et al., 1999; Cowan et al., 2009). In contrast, another study found no significant difference in velocity with increasing weight of the wheelchair (Bednarczyk et al., 1994). ~~It may be that the~~The combination of the additional weight of the device, its distribution on the chair, ~~as well as~~and the added rolling resistance of the drive wheel on the ground could ~~both~~ have contributed to these results.

Methodologically, this is the first study we were able to identify that used a treadmill and an instrumented wheel to measure stopping forces during wheelchair propulsion. Understanding how much effort to stop a wheelchair may be just as important as minimising forces and physiological work during propulsion. This is especially true for determining who might be suitable to use this kind of power assist drive, as the ability to stop a wheelchair is as important as the ability to getting it going, particularly for those with limited strength. Thus, creating a protocol that ensured all participants were wheeling at the same speed prior to stopping was essential. Our approach using a treadmill is unique to the literature, and can inform future research in this area.

Study Limitations

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

CONCLUSION

This study showed that participants were able to reach a complete stop in a shorter distance with less force with the device, although the reduced stopping distance may not be clinically meaningful. ~~. Although this finding was statistically significant, it may not be clinically significant.~~ ~~However~~Furthermore, -P~~, p~~articipants did not use ~~used~~ more force when initiating movement with the device attached. From a biomechanical perspective, the device may be better for stopping, especially in terms of potential overuse injuries in the upper extremities. ~~, but may also add stress to upper extremities in conditions where frequent stopping and starting occur.~~ However, further research is needed ~~Since the device was designed for longer distances in wheelchair users, the next step is~~ to examine the efficacy and utility ~~benefits~~ of the device with wheelchair users.

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

ABSTRACT

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 minimum force 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 starting force (% Body Weight (BW)), maximum velocity with a single push, stopping distance, and peak braking force (%BW). Participants did not have significantly increased starting force or maximum velocity with a single push using the add on. Participants had significantly shorter stopping distance (P=0.045) (η^2 =0.163) and reduced peak breaking force (p=0.02) (η^2 =0.351) using 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. The next step is to evaluate its applicability and clinical relevance by investigating wheelchair users in their natural environments.

INTRODUCTION

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

PAPAWs are motorized wheels that are attached to manual wheelchairs (Kloosterman et al., 2013; Levy et al., 2004). With each push on the handrims, the motors within the wheels engage, allowing the individual to use less effort per push. There has been considerable research on PAPAWs, which has highlighted the potential benefits of the device (Algood et al., 2004; Algood et al., 2005; Arva et al., 2001; Best et al., 2006; Cooper et al., 2001; Corfman et al., 2003; Ding et al., 2008; Fitzgerald et al., 2003, Giesbrecht et al., 2009; Kloosterman et al., 2012; Levy et al., 2010; Lighthall-Haubert et al., 2009; Nash et al., 2008). For example, among those with spinal cord injuries who had shoulder pain, PAPAWs reduced energy costs, perceived exertion, and allowed users to increase distance propelled significantly. However, one disadvantage of PAPAWs is the added weight of the wheels (approximately 26kg) (Nash et al., 2008).

The SmartDrive™ (MAX Mobility, 2016) is a relatively new power assist device for manual wheelchairs. As illustrated in Figure 1, the MX1 model includes two components: a battery that is mounted under the seat, and a drive wheel that hooks on to the camber tube of the wheelchair (Figure 1). To engage the drive wheel, the user needs to exceed a minimum acceleration threshold, at which point the drive wheel will begin to turn. Unlike PAPAWs, the sensors to detect acceleration of the chair are not located in the handrims but in the drive wheel. The drive has two modes: indoor and outdoor. Once activated, the drive will continue to propel the wheelchair at the highest velocity the user has achieved. This is in contrast to the PAPAWs, which continue to need hand-rim input in order to continue propelling the individual. To stop the wheelchair in the indoor mode, users need to apply sufficient braking force through the hand rims to exceed the device's deceleration threshold, at which point the drive disengages. In contrast, to stop the wheelchair in the outdoor mode, the user needs to push a stop button and hold the hand rims. The outdoor mode is useful, because the drive will cut off in the indoor mode when there are decelerations above a certain threshold (e.g., thresholds, curb cuts, cracks in the sidewalk). The owner's manual indicates it can help propel wheelchairs up to 8.85km/hr on level ground or 8.0km/hr on a 6^{o} incline. The SmartDrive™ is lighter than PAPAWs (approximately 9kg), which may make it easier to use (Levy et al., 2004).

Although it might be anticipated that a rear mounted power assist would produce similar benefits as PAPAWs, the device's lighter weight and unique design warrants specific attention. Clinically, it has been observed that some wheelchair users cannot start the device, or more problematically, may have difficulty stopping it. Therefore, our study aimed to compare the force required to start and stop a wheelchair with and without the drive at different speeds. Additionally, the stopping distance and peak total force after a single push were measured. Given that force = mass x acceleration, we anticipated either increased force would be required with the device (in light of its added mass) or deceleration would be reduced (and stopping distance would increase).

METHODS

The study used a cross-over study design, in which participants were evaluated with and without the drive. The local university and hospital ethics board approved the study.

Participants

Able-bodied participants were only included in order to reduce heterogeneity that occurs with using participants with disabilities and to reduce the likelihood of injuries during sudden stops with the device. Twelve male and twelve female able-bodied individuals were recruited with a mean age of 30.5 ± 12.4 years (mean age ± SD) (See Table 1). Seven of the participants had some experience in using a manual wheelchair (i.e. sports day events, family owned wheelchairs). The inclusion criteria for the study was that participants had to be over 18 years of age, ambulatory, English speaking, and without any upper/lower extremity physical or neurologic problems. Participants were recruited via posters on bulletin boards and the website at our local hospital and research centre.

[Insert Table 1]

Data Collection

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

The right rear wheel of a rigid ultralight wheelchair (Tilite TR™) was replaced with a Smart$^{\text{WHEEL}}$. This instrumented wheel uses six strain gauges to measure 3D forces and moments applied to the pushrim. Data from the SmartWheel™ were collected at 240Hz using proprietary software and filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 20 Hz. Variables collected with the SmartWheel™ included three dimensional forces (Newtons), total force ($\sqrt{(Fx^2+Fy^2+Fz^2)}$), tangential force (force acting on forward propulsion), cadence (cycles/s), push angle

(angle (degrees) that the hand was in contact with the pushrim during the propulsion phase), velocity (m/s), and mechanical efficiency (tangential force^2/total force^2). These data were used to calculate *peak total force* (% body weight) and *speed* (m/s) and, *stopping distance* (meters).

Protocol

Participants had the opportunity to get familiar with the manual wheelchair before data collection began for approximately 5-10 minutes with and without the drive. Since this part of the study was primarily about stopping, instruction was not provided on specific propulsion techniques. The same wheelchair was used for all participants. Rear tires were inflated to 100 psi prior to testing. The participants were randomized to begin the study either with or without the drive attached to the wheelchair operating in the indoor mode. *Stopping distance* data were collected at two different speeds (3.5 km/hour and 6.0 km/h) with two trials at each speed using a wheelchair treadmill (MaxMobility) at 0.5 degree incline to standardize velocities. Participants were instructed to propel on the treadmill until each speed was reached and maintained for a minimum of three seconds. The researcher then asked the participant to stop the wheelchair while simultaneously turning off the treadmill. In a separate test, to measure *starting peak total forces* and *peak speed*, participants were asked to propel the chair with “one light push, in order to get the wheelchair going” from stationary on a level tile floor with and without the drive.

Participants were asked to repeat the light push task until they were able to accelerate the chair to engage the drive.

Statistical Analysis

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

RESULTS

Stopping (Stopping distance and peak total force)

The *stopping distances* at both speeds with and without the drive are reported in Table 2, and the values are represented in Figure 2a. The analysis indicated a *stopping distance* normalized for body weight (%BW) was significantly less (F=16.098, p=0.01). This is represented in Figure 2b. The *stopping distances* at both 3.5 km/hr and 6.0 km/hr were significantly shorter with the drive attached (F=4.475, p=0.045). The normalized stopping distances are represented in Figure 2c. All of the effect sizes are considered large ($\eta^2 > 0.138$). The *peak total stopping force* required for both speeds, was significantly reduced when using the drive (F=12.465, p=0.02). This is represented in Figure 2c.

[Insert Table 2, figure 2]

Starting (Peak force and peak velocity)

The *starting peak total force* and *peak speed* are reported in Table 3. Participants did not use a statistically significantly greater force (%BW) with the drive attached (p=0.245), nor was there a significant difference in peak speed at start up between conditions (p=0.088).

[Insert Table 3]

DISCUSSION

This is the first study to investigate the kinetic forces when using a rear mounted powered drive wheel affixed to a manual wheelchair. It is also the first study that the authors are aware of that studied stopping forces during wheelchair use rather than typical propulsive forces.

Stopping Distance and Peak Force to Stop

Although it was anticipated greater force would be required to stop the device due to the added weight of the drive, this hypothesis was not supported. Instead, peak stopping force was significantly reduced with the drive. . This is surprising given the additional mass of the SmartDrive™ was ~9kg and theoretically should have made stopping more difficult. . h Since participants were able to stop in significantly less distance; however, this reduction in stopping force may have been due to the inertia and rolling resistance of the drive wheel. Studies have found that solid tires have significantly increased rolling resistance compared solid tires (de Groot et al., 2013) and demonstrate greater increase in rolling resistance with added mass (Kwarciak et al., 2009). . Given that the drive wheel is solid and knobby (given its omni-directional rollers) and has a large foot print, this could add rolling resistance to the wheelchair, increasing the chair’s drag and contributing to the shorter stopping distance with the same amount of force.

Although the stopping distance was significantly shorter with the drive, it is unclear whether a decrease in stopping distance of 3 cm at 3.5 km/h or 5 cm at 6 km/h would be clinically meaningful. However, this finding is important as it demonstrates that the device does not increase stopping distances, which would pose a potential safety concern. This is particularly important for those individuals who have limited grip strength for braking, such as those with higher-level spinal cord injuries. In theory, as long as individuals are able to generate sufficient breaking forces to stop the drive, they will be able to come to a stop in less distance.

Peak Force on First Push and Peak Speed

The peak force on first push was not significantly larger when using the drive and there was no difference in speed on first push. Our value for peak force on first push were similar to those found previously (i.e.,1.23 N/kg (Cowan et al., 2008).For our values of peak force on first push, the p-value trended toward significance, so a larger sample size may have been required. If larger starting forces are required, the drive could potentially be fatiguing if it is frequently being engaged and disengaged (e.g. manoeuvring in small spaces). The added weight and drag may result in increased work under these circumstances, especially when trying to initiate the drive going up hills or on rougher surfaces. In contrast, for longer distances the drive might require less energy as only steering is required rather than repetitive strokes used for typical manual propulsion.

It is difficult to determine whether it is the increased mass or increased drag of the drive is primarily responsible for the study findings. There is conflicting evidence about the effect of adding mass alone to a wheelchair. A study by de Groot et al. (2013) found that extra mass alone added to a manual wheelchair did not have an effect on power output or physical strain; however, their study measured forces during steady-state exercise testing, and they acknowledged there might be differences in physical strain during starting and stopping. Furthermore, in their protocol the extra mass (+5kg, +10kg) was placed below the seat directly above the rear axis, whereas the added weight of the drive is distributed below the seat (battery pack) and resting on the ground (drive wheel), resulting in some additional drag. Some studies have shown reduced velocity with increasing weight (7.80-9.05kg), without altering changes in normal force on either the front casters or rear wheels) of the wheelchair (Beekman et al., 1999; Cowan et al., 2009). In contrast, another study found no significant difference in velocity with increasing weight of the wheelchair (Bednarczyk et al., 1994). The combination of the additional weight of the device, its distribution on the chair, and the added rolling resistance of the drive wheel on the ground could have contributed to these results.

Methodologically, this is the first study we were able to identify that used a treadmill and an instrumented wheel to measure stopping forces during wheelchair propulsion. Understanding how much effort to stop a wheelchair may be just as important as minimising forces and physiological work during propulsion. This is especially true for determining who might be suitable to use this kind of power assist drive, as the ability to stop a wheelchair is as important as the ability to getting it going, particularly for those with limited strength. Thus, creating a protocol that ensured all participants were wheeling at the same speed prior to stopping was essential. Our approach using a treadmill is unique to the literature, and can inform future research in this area.

Study Limitations

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

CONCLUSION

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

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Figure 1. SmartDrive power assist.

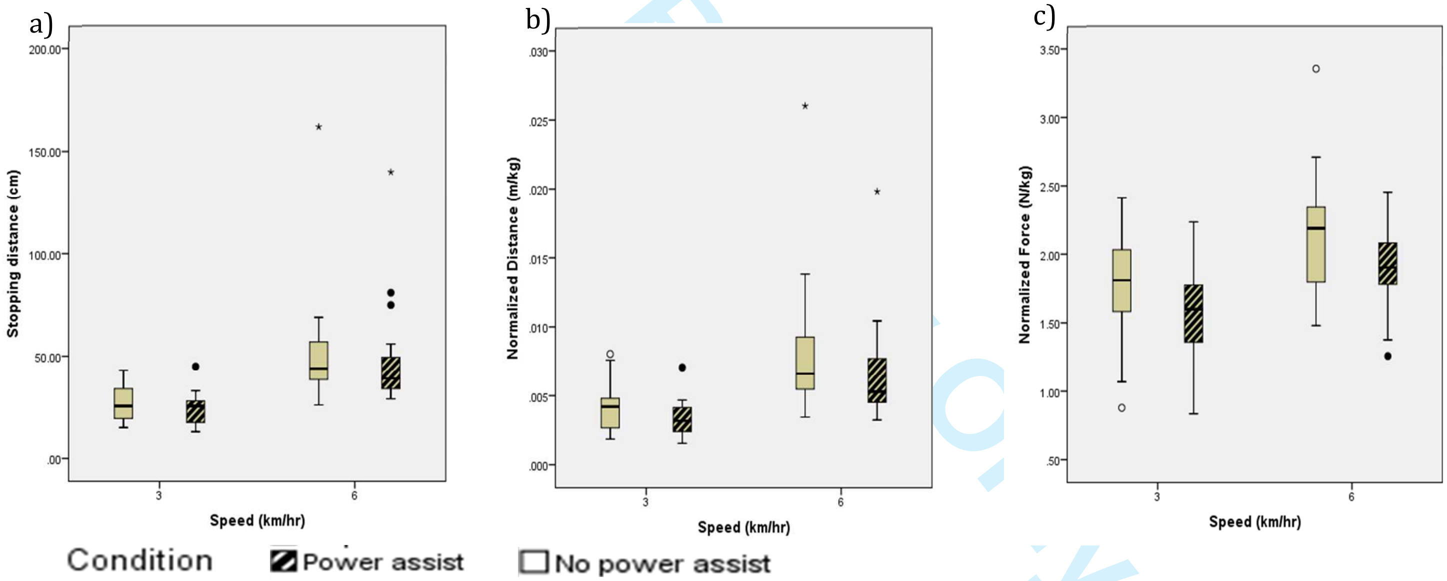

Figure 2. Box plots displaying stopping distances and peak forces at different speeds with and without the SmartDrive power assist (n=24). a) Stopping distance (cm) vs. speed (km/hour). b) Normalized stopping distance (m/kg) vs. speed (km/hour). c) Normalized peak stopping force (N/kg) vs. speed (km/hour).

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 η2)
	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