Benchmarking of power-assist wheelchair systems

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INTRODUCTION

A power-assist wheelchair system is a hybrid between a manual and power wheelchair that consists of an electric-assist system that can be easily mounted on a conventional manual wheelchair [1]. The past decade has seen an explosion in the development of new power-assist wheelchair systems. This market growth, coupled with the demonstrated significant benefit of power-assist on the health and mobility of manual wheelchairs users [1] means that research in this field of technology is timely and will reveal more about how power-assist systems benefit wheelchair users and how new designs can address potential limitations of existing products.

Two recent systems that have garnered substantial industry support are the SmartDrive MX2+ and the Alber Twion power-assist wheels. With the advent of these products on the market, the potential for research to characterize the mechanical properties of these devices exists. Specifically, the torque, speed and power of these systems in various loading conditions is not known beyond the basic information provided by the device manufacturers. An example of this might be how the SmartDrive MX2+ performs on a section of steep hill with different weight users. Understanding the electromechanical characteristics of these systems is important for several reasons, including:

1) Providing a better understanding of the benefit of power-assist to the wheelchair user. A study in 2016 concluded that available pushrim-assisted power-assist systems are effective in reducing shoulder load and partly effective in reducing force generation in the extremes of shoulder motion during start-up [2]. Characterizing the electromechanical output of these power-assist systems will provide insight into their ability in different loading scenarios, such as climbing a slope or other high-torque situations.

2) Matching system performance to user needs. This is important in the design of power-assist systems as the system mass has been shown to be a significant detriment to the wheelchair user because it increases the total mass of the chair [1], therefore requiring more propulsive force when the system is not providing assist and increasing the difficulty of tasks such as car transfers. Investigating the mechanical output of these systems and matching this data to user feedback could yield insight into real and perceived performance of power-assist systems for future improved designs, perhaps including the design of lighter systems.

3) The verification of analysis concerning the power, torque and speed requirements of a power-assist system. To improve power-assist systems, we need to characterize current product capabilities, and have the tools for development benchmarking when iterating new design solutions.

The purpose of this study was therefore to verify the functionality of a laboratory wheelchair dynamometer and to benchmark the electromechanical performance characteristics of the SmartDrive MX2+ and Alber Twion systems under a range of torque and speed conditions.

METHODS

Dynamometer

Absorption dynamometers are used to absorb and record energy from a rotating input by varying the amount of load applied to the input through a braking element. To characterize the energy provided by the power-assist systems and the resulting wheelchair dynamics at a range of torque and speed settings, an absorption dynamometer was designed and manufactured (Figure 1). A hysteresis brake (Magnetic Technologies Ltd. EB-1750M-2DS) was used as the absorption unit. The brake was coupled to a roller where any power-assist system and wheelchair can be installed and tested. A Hall Effect sensor (Littelfuse 55505) and frequency-to-voltage converter (Texas Instruments LM2907) were used to measure the roller speed, while a load cell (Anyload 563YH, A2A Amplifier) and torque arm were used to measure the torque. The two inputs were recorded using a data acquisition device (Measurement Computing USB-1208 FS). The data was sampled at 750 Hz for both channels.

Figure 1: Hysteresis Brake Dynamometer

Power-Assist System Background

While the SmartDrive MX2+ and the Alber Twion can both be classified as power-assist systems, the nature of their assist differs substantially. The SmartDrive MX2+ provides a constant velocity assist for a prolonged duration, regardless of user force input on the pushrims. The SmartDrive MX2+ is controlled using a separate accessory wristband. The user double taps the wristband to start ramping up the speed. They then tap to coast at the current speed and then double tap to stop [3]. The result is a control method that functions well for instances where the user requires prolonged power-assistance, such as traversing a city block or carpeted hallway.

In contrast, the Alber Twion wheels act more as a direct push-assist device, using sensing pushrims to provide additional assistance once a user push has been detected. The result is a dynamic power-assist that essentially amplifies a user's push. For the Twion to attain the same type of long distance continual power-assist similar to the SmartDrive, the user must continually push the pushrims to maintain velocity, similar to pushing without assist.

The difference in assist types necessitated different testing methods for each system. The SmartDrive was tested using testing methods similar to conventional electric motors, where the steady-state speed and torque are recorded for discrete intervals to form a graph of the continuous output speed, power and torque. Since the Twion cannot output a continuous power due to its dynamic functionality, the Twion was tested over a range of torques at the same discrete braking torque values as tested for the SmartDrive. A researcher pushed the Twion wheels by providing input to the pushrims in a manner analogous to conventional wheeling. The different testing methods necessitated different procedures, processing filters and post-processing, which is detailed in the following sections.

SmartDrive Testing Procedure

The SmartDrive was installed on a test wheelchair and the drive wheel of the SmartDrive was located on the dynamometer roller. The maximum speed setting was used for all testing (5.5 mph). The SmartDrive was accelerated to the constant maximum speed at no braking torque. The recorded torque at this no-load condition includes the resisting torque from the dynamometer friction. The dynamometer braking torque was then increased in approximately 2 Nm increments up to 10 Nm measured at the roller. The SmartDrive increased its torque output to overcome the braking torque, which resulted in a decrease in output speed. The speed was settled to a steady-state value after every torque increase, resulting in discrete steady-state measurements for multiple torque and speed values. This process was continued until the maximum torque of the hysteresis brake was applied. A total of ten tests were performed with the SmartDrive using this method.

The results of the SmartDrive testing were processed using a low-pass 2^{nd} order Butterworth filter with a cut-off frequency of 1 Hz and then downsampled to 1 Hz (Matlab, Mathworks Inc). The mechanical output power of the SmartDrive was then computed by multiplying the torque and velocity. A linear regression was performed on the torque vs. speed data, based on the presence of a linear proportional relationship of these variables for a brushless DC motor [4].

Twion Testing Procedure

Both wheels of the Alber Twion system were installed on a test wheelchair and the wheels were located on the roller of the dynamometer. The testing started with a zero-braking torque input. The researcher was seated in the test wheelchair and pushed the Twion pushrims five times, at which point the braking torque was increased to by approximately 2 Nm incrementally up to 10 Nm measured at the roller. Five pushes were conducted at each torque increment for a total of 30 pushes per test. The Twion speed and output torque were recorded for each resisting torque setting.

The results of the Twion testing were processed using a low-pass 2^{nd} order Butterworth filter with a cut-off frequency set at 40 Hz. The angular acceleration was then calculated using the angular velocity data and numerical differentiation in MATLAB. The torque from system inertia was then computed by multiplying the inertia and the angular acceleration. The inertial torque, measured torque and friction torques were then summed to compute the final motor output torque.

RESULTS

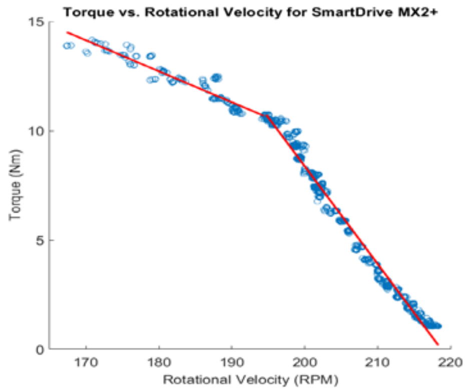

Figure 2: Torque vs. Rotational Velocity for SmartDrive MX2+

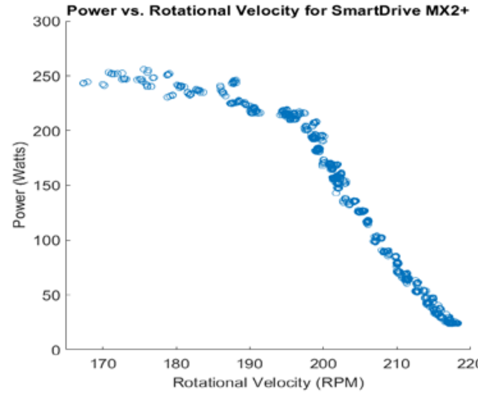

Figure 3: Power vs. Rotational Velocity for SmartDrive MX2+

SmartDrive Results

The results of the SmartDrive testing are shown in Figure 2 and Figure 3. The SmartDrive achieved a peak torque of 14.2 Nm at 170.8 RPM, resulting in a peak power of 253.0 Watts (values of torque and speed presented in Figures 2 & 3 are measured at the 7.5 inch diameter SmartDrive wheel). The maximum torque value corresponds to a maximum linear propulsive force for a wheelchair user of 148.9 N at 6.1 km/hr. At approximately 10.5 Nm of torque output the linear torque speed relationship of the SmartDrive changes, which is shown by the line in red in Figure 2. This change ultimately limits the motor output to a maximum of approx. 250 Watts, which is the quoted maximum power of the SmartDrive system [3].

Twion Results

Figure 4 shows the results of the Twion testing when a resisting torque of 7 Nm was applied to the system at the roller. The plot shows a large input torque before the speed changes, a result of the user's input push. At 0.5 seconds the rotational speed is increasing and the torque is decreasing while the peak power is observed. This is the region where power is being supplied by the user and the Twion. At one second there is minimal change in the rotational speed and relatively constant torque and power. The power at this point is 120 Watts combined for both wheels, in-line with the reported power output of the Twion system [5], indicating that the Twion is the main source of propulsion. The Twion output torque at this point is approximately 28 Nm, when considering both wheels together. This torque corresponds to an equivalent linear propulsive force of a wheelchair user of 94.1 N at 4.5 km/hr.

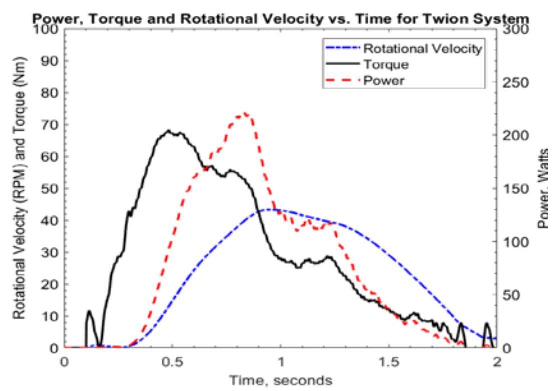

Figure 4: Torque, Rotational Velocity and Power vs. Time for Alber Twion System

DISCUSSION

The results of this testing demonstrate that the calibrated hysteresis brake dynamometer can be used to test wheelchair power-assist systems under a variety of loading scenarios. The preliminary benchmarking completed in this study provides information about the performance of the SmartDrive and Twion power-assist systems and highlights the substantial differences in functionality in these systems. The performance characteristics captured in this study can now be used to further inform dynamic analysis into the theoretical performance requirements of a power-assist system, e.g. a 100 kg person with a 20 kg wheelchair pushing up a slope of 6° at a speed of 4 km/hr requires approximately 175 Watts of continuous power.

In the case of the SmartDrive, the results of the testing show that the device is designed to output relatively high power through a large range of speeds and torques. For example, the SmartDrive can output greater than 10 Nm of torque from 150 RPM to 190 RPM. This means that the SmartDrive can output greater than 100 N of propulsive force for constant forward speeds less than 6.8 km/hr, translating to significantly beneficial assistive power in scenarios such as hills or sloped surfaces. For perspective, the data indicates that the SmartDrive is able to propel a 100 kg user with a 20 kg wheelchair up a 4.8° concrete ramp at approximately 7 km/hr. The SmartDrive's ability to operate at greater than 200 watts for a significant portion of its high-torque operating curve in Figures 2 & 3 indicate that the device is especially well designed for power output in high torque scenarios such as climbing hills and steep grades. However, the SmartDrive system power may be limited in its assistive effects by its inherent design using its own weight to generate traction in certain situations, e.g. slick surfaces or loose ground [3] although this was not tested here.

The results of the Twion testing confirm the device's capability for intended use as a power-assist device. The user of the Twion must always engage the device with a torque input before receiving power. This means that the peak torque of 70 Nm in Figure 4 is the sum of two components, the user input torque and the Twion assistive torque. The torque at this peak could indicate that the user in high torque scenarios such as starting on a hill must push hard before receiving assistive power. This could also be a result of the Twion using force-sensing pushrims [5] which would require a large force input on an incline due to the increased propulsion requirement. In contrast, the Alber E-Motion power-assist system uses pushrim sensing, but provides a fixed level of assist regardless of the magnitude of user force input [6]. Based on the results of this study, the Twion system can supply assistive power for high-torque scenarios such as an incline, but requires continued user input with proportional force to maintain propulsion. For reference, the Twion system can provide a propulsive force equivalent to a 100 kg wheelchair user with a 20 kg wheelchair pushing up a 4.8° concrete ramp at a speed of 3 km/hr.

The verification and deployment of the dynamometer system resulting from this study will additionally allow for the testing of many types of power-assist devices. Resisting torques based on real-world conditions such as sloped ramp can be input to the system to see how it performs under load. Additionally, torque requirements based on user and wheelchair mass could be tested by varying the input braking torque. An example of this might be to quantify variations in the SmartDrive performance on a wheelchair ramp for a 150 lb and a 300 lb occupant. Battery life testing also presents another potential area for research with the dynamometer. Additionally, the dynamometer presents a method for testing prototypes of power-assist systems, using repeatable input conditions, and allows for benchmarking potential prototypes against currently available systems.

CONCLUSIONS

A hysteresis brake dynamometer was manufactured and used to benchmark two power-assist systems, the SmartDrive MX2+ and the Alber Twion. The results of this study show that both power-assist systems meet their expected output torque and power specifications, and the dynamometer recorded output torque, power and speed of the power-assist system under test. The testing confirmed that the SmartDrive is a high-power system, well suited to high torque and speed applications; and the Twion is a very responsive power-assist system, providing assistive torque in response to a user's pushrim input. The resulting data from this study can be used used to further inform dynamic analysis for the design of future power-assist systems, and the dynamometer can be used to test these systems under a range of loading conditions appropriate for real-world mobility situations.

ACKNOWLEDGEMENTS

This research was completed with contributions from the Rick Hansen Institute, the Natural Sciences and Engineering Research Council of Canada, MITACS and the Canada Research Chairs.

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