Development and evaluation of a gyroscope-based wheel rotation monitor for manual wheelchair users

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Objective: To develop and evaluate a wireless gyroscope-based wheel rotation monitor (G-WRM) that can estimate speeds and distances traveled by wheelchair users during regular wheelchair propulsion as well as wheelchair sports such as handcycling, and provide users with real-time feedback through a smartphone application.

Methods: The speeds and the distances estimated by the G-WRM were compared with the criterion measures by calculating absolute difference, mean difference, and percentage errors during a series of laboratory-based tests. Intraclass correlations (ICC) and the Bland–Altman plots were also used to assess the agreements between the G-WRM and the criterion measures. In addition, battery life and wireless data transmission tests under a number of usage conditions were performed.

Results: The percentage errors for the angular velocities, speeds, and distances obtained from three prototype G-WRMs were less than 3% for all the test trials. The high ICC values (ICC (3,1) > 0.94) and the Bland–Altman plots indicate excellent agreement between the estimated speeds and distances by the G-WRMs and the criterion measures. The battery life tests showed that the device could last for 35 hours in wireless mode and 139 hours in secure digital card mode. The wireless data transmission tests indicated less than 0.3% of data loss.

Conclusion: The results indicate that the G-WRM is an appropriate tool for tracking a spectrum of wheelchair-related activities from regular wheelchair propulsion to wheelchair sports such as handcycling. The real-time feedback provided by the G-WRM can help wheelchair users self-monitor their everyday activities.

Keywords: Wheelchairs, Handcycle, Wheelchair Propulsion, Activity Monitor, Wireless, Sensors, Smartphones, Spinal cord injuries, Paraplegia, Wheelchair sports

Introduction

Wheeled mobility is associated with the majority of wheelchair related Physical Activities (PAs) and activities of daily living in manual wheelchair users (MWUs). Research has shown that wheel rotation monitors can be used to assess mobility characteristics, activity levels, and wheelchair use of MWUs in laboratory, community and nursing home settings.^{1–4} However, there are only a limited number of monitoring tools available for manual wheelchair users (MWUs).^{2–6} This is especially striking as the general population can choose from a wide array of activity monitors to track their activities in the community in terms of steps, intensity of PA, duration of PA, and energy expenditure.^{7–11} The

availability of activity monitors for MWUs can help researchers and clinicians in the fields of rehabilitation science, kinesiology, and health and physical activity to study mobility characteristics and evaluate mobility related interventions in this population. In addition, such tools could facilitate self-monitoring among MWUs by providing accurate feedback regarding the speeds and distances travelled during wheelchair-related PAs. Research has shown that moderate intensity activities are sufficient to maintain fitness and prevent cardiovascular diseases for MWUs.^{12,13}

The existing measurement tools for MWUs have varying sensitivity and accuracy in estimating speeds and distances traveled by wheelchair users. These tools either use a pendulum and reed switch-based method² or accelerometer-based method^{3,4,6} to sense wheel rotations. Tolerico *et al.*² evaluated the validity of a

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pendulum and reed switch-based device on a double drum that simulates wheelchair use. The percentage errors for the device when estimating the speeds varying from 0.8 to 1.8 m/s were found to be 1 and 5%, respectively. Coulter *et al.*⁴ investigated a wheel-mounted tri-axial accelerometer and found the device was highly accurate in estimating wheel revolutions, absolute angle and duration of movement (ICC (2,1) > 0.999, 0.999, 0.981, respectively) when 14 wheelchair users were asked to propel their wheelchairs forward and backward along a course. Sonenblum *et al.*³ evaluated a wheel-mounted tri-axial accelerometer in detecting wheelchair movements and estimating distances traveled. They found that the device had accuracy greater than 90% for various wheelchair and wheel types, propulsion techniques, speeds, and wheelchair-related activities of daily living including propulsion, food preparation, handwashing, loading a dishwasher, entering a bathroom stall, and using an elevator. In another study, Gendle *et al.* mounted a tri-axial accelerometer below the wheelchair seat to assess PA of wheelchair users.⁶ The research found that the activity counts derived from the accelerometer were significantly different between light and moderate effort ($P < 0.01$) trials with high between-trial reliability ($r \geq 0.85$). The difference between the studies by Sonenblum *et al.* and Gendle *et al.* was the placement of the accelerometer on the wheel¹³ versus under the wheelchair seat¹⁴ resulting in wheel rotation measurement and the wheelchair acceleration measurement, respectively. None of these activity monitors has indicated that they can estimate speeds and distances over a spectrum of wheelchair-related PAs from regular wheelchair propulsion to wheelchair sports such as

handcycling. Also, these monitors were not designed to provide real-time feedback to wheelchair users.

In this study, we have developed and evaluated a wireless gyroscope-based wheel rotation monitor (G-WRM) that can estimate speeds and distances traveled by wheelchair users during regular wheelchair propulsion as well as wheelchair sports such as handcycling and provide real-time feedback to users through a smartphone application. We evaluated the validity of the G-WRM in measuring angular velocities and estimating speeds and distances through a series of laboratory-based tests. We also conducted a series of tests on the battery life and wireless data transmission of the G-WRM.

Methods

Development

The G-WRM uses a gyroscope to detect angular velocities of the wheelchair's wheel, which are then converted to wheel revolutions, and distances and speeds traveled by wheelchair users. The choice of using a gyroscope sensor instead of an accelerometer was based on a pilot study where we tested a wheel-mounted tri-axial accelerometer (range: $\pm 39.24 \text{ m/s}^2$ or $\pm 4 \text{ g}$) and the G-WRM for a range of speeds during a handcycling trial. Fig. 1 shows the results of the pilot study for the handcycling trial, which indicated that the wheel rotation pattern using a three axis accelerometer was clear (sinusoidal pattern) for low speeds, but not for high speeds. The results showed that with the increase of traveling speeds, the accelerometer signals of the two axes in the plane of wheel rotation separated from one another with one of them becoming saturated with consistent low values. In addition, the acceleration sensed by the accelerometer combined the wheel

Figure 1 Acceleration and speed plots from a three axis accelerometer and a G-WRM, respectively, for handcycling at low and high speeds.

Figure 2 G-WRM secured to the spokes of a manual wheelchair and a handcycle.

rotation movements and the linear forward or backward movements, which could be computationally expensive to differentiate if real-time feedback is to be provided. The same problem also exists with the pendulum and reed switch design,² which can provide relatively accurate estimation of distances and speeds traveled by wheelchair users in the community settings. However, laboratory tests have shown that this method could underestimate speeds when a wheelchair travels at speeds greater than 2.5 m/s (5.6 miles per hour).¹⁵ Our observation of the problem with the existing devices at higher speeds has led us to design and develop a gyroscope based G-WRM that can capture a range of speeds from wheelchair propulsion to handcycling.

Instruments

The G-WRM (Fig. 2) is a self-enclosed rechargeable device that can be attached to the spokes of the wheel of a wheelchair or a handcycle. The G-WRM was built upon our previous pendulum and reed switch device to reduce the development time. The G-WRM contains six reed switches mounted 60° apart on a printed circuit board and a two-axis gyroscope with low ($\pm 1500^\circ/\text{second}$) and high angular velocity ranges ($\pm 6000^\circ/\text{second}$) allowing us to capture speeds up to 64 km per hour (40 miles per hour) for a 0.61 m (24-inch) wheel. The gyroscope can be sampled with frequencies varying from 64 samples per second (64 Hz) to 1 sample per minute to suit various speeds from wheelchair sports such as handcycling and wheelchair racing to everyday wheelchair propulsion. The reed switches are triggered by a pendulum and magnet assembly, which is mounted in the G-WRM casing. However, the reed switches were not used to estimate speeds and distances in this study. We only used the G-WRM's gyroscope to measure angular velocities which was

then converted to speeds and distances traveled. Furthermore, the G-WRM has a Bluetooth communication module through which the mobility data can be sent to a smartphone and a micro secure digital (SD) memory card that can store the mobility data locally. The G-WRM is also paired with an Android-based mobile application (Fig. 3), which was designed to allow wheelchair users to receive real-time feedback on their movements including distance, speed, and duration of mobility.¹⁶

Figure 3 The Android application for the G-WRM.

Figure 4 Plot of raw sensor values from the G-WRM's gyroscope (solid line) and during various angular velocity tests (dotted line) on the CNC lathe.

Calibration protocol

The calibration protocol involved collecting raw gyroscope data from the G-WRM when the device was attached on a ST20 Computer Numerically Controlled (CNC) lathe (HAAS Automation, Inc., Oxnard, CA, USA) that was set at known angular velocities (Fig. 4). The gyroscope data were collected from six repeated trials of 2 minutes at speeds of 40, 60 and 80 rotations per minute (rpm), respectively, in both clockwise (forward) and counterclockwise (reverse) directions. The gyroscope data were then used to develop offset values and basic calibration equations for both clockwise and counterclockwise directions to maximize sensitivity of the gyroscope to detect various angular velocities. The angular velocity information from the gyroscope was later used to estimate linear speeds and distances traveled by a wheelchair user.

Experimental protocol

We evaluated the validity of three randomly chosen G-WRM prototypes in measuring angular velocities, and estimating speeds and distances traveled by a wheelchair using a number of laboratory-based tests. We assessed the G-WRM's wireless function by measuring data loss. We also evaluated the battery capacity of the G-WRM in wireless mode and storage mode (via the SD card), respectively.

Validity of measuring wheelchair movements

CNC lathe test

To evaluate the validity of the G-WRM in measuring angular velocities, we secured each G-WRM to the chuck of a lathe and ran the lathe for 10 minutes of duration each at angular velocities of 40, 60, and 80 rpm in both clockwise (forward) and counterclockwise (reverse) directions, respectively. Each test condition was repeated three times.

Double-drum test

To evaluate the validity of the G-WRM in estimating linear speeds, we secured each G-WRM to the spokes of a manual wheelchair set up on a double drum (ISO 7176-08)¹⁷ with drive wheels on one drum and castors on the other drum. The two drums run at slightly different velocities, with the back running at 1 m/second (2.24 miles per hour) and the front at 0.95 m/second (2.12 miles per hour), in order to simulate road hazards commonly encountered by wheelchair users. The test was conducted with and without slats (Fig. 5) to simulate propulsion during curb drops and flat surface, respectively. The tests were repeated twice for a duration of 6 hours in both forward and backward directions.

Wheelchair propulsion test

To evaluate the validity of the G-WRM in estimating distances traveled during regular wheelchair propulsion,

Figure 5 Plot of speed estimated by the G-WRM on double drum with and without slats.

we conducted a total of 54 trials (see Table 1) for nine tasks with each task repeating six times on concrete flooring surface. During all these trials, an investigator who is experienced in wheelchair use propelled either a manual wheelchair with a camber of 2.5° or a rugby chair with a camber of 15.5° . For the first 48 trials, we used the measured distance via a tape measure between the start and end points as the criterion measure. The G-WRMs were secured to the spokes of the manual wheelchair's or rugby chair's wheel. For the last six trials, we used

the measured distance via a SmartWheel (Three River Holdings, Inc. Mesa, AZ, USA) and a three-dimensional passive motion capture system (model MX, Vicon Peak; Lake Forest, CA, USA) as the criterion measure. The G-WRMs were secured to the spokes of the SmartWheel. The SmartWheel is a clinical tool that can measure wheelchair propulsion kinetics including distances traveled. We followed standardized calibration procedures for VICON and SmartWheel as per the manufacturer's specifications.

Table 1 Wheelchair propulsion tasks performed

Sl. no.	Propulsion task
1	Propelling straight forwards (10 m) on a flat tile surface with a camber of 2.5°
2	Propelling straight forwards (15 m) on a flat tile surface with a camber of 2.5°
3	Propelling straight forwards (20 m) on a flat tile surface with a camber of 2.5°
4	Propelling straight backwards (10 m) on a flat tile surface with a camber of 2.5°
5	Propelling up and down a ramp (slope of 2.7° , length 12.19 m) on a flat tile surface with a camber of 2.5°
6	Propelling straight forwards (10 m) on a flat tile surface with a camber of 15.5°
7	Propelling straight forwards (15 m) on a flat tile surface with a camber of 15.5°
8	Propelling straight forwards (20 m) on a flat tile surface with a camber of 15.5°
9	Propelling straight forwards (18 m) on a flat tile surface with a camber of 2.5°

Handcycling test

To evaluate the validity of the G-WRM in estimating distances traveled during handcycling, we attached the G-WRM to the spokes of an Invacare Top End Force R X handcycle (Invacare Corporation, Elyria, OH, USA). An investigator who is an experienced wheelchair user with disability performed handcycling for nine laps on a cycling track with asphalt concrete surface. The G-WRM 1 was secured to the inner wheel and the G-WRMs 2 and 3 were secured to the outer wheel with respect to the center of the track. For this test, we used the total track length of 7.24 km (0.805 km for 9 laps) as the criterion measure.

Battery life test

We evaluated the G-WRM's battery life by performing tests in wireless mode where the data were sent

continuously to a smartphone and in standalone SD card mode where the data were stored locally without wireless transmission. During the wireless mode testing, we conducted six trials for each G-WRM where we collected data continuously through a smartphone at 64 and 1 Hz for three times, respectively, until the battery was drained. During the standalone SD card mode testing, we conducted three trials for each G-WRM where we sampled the data continuously at 64 Hz and stored the data in the SD card at 1 Hz for three times until the battery was drained.

Wireless data transmission test

We evaluated the G-WRM's Bluetooth performance by examining the data loss rate. We conducted nine trials for each G-WRM where we transmitted the data sampled at 64 Hz from the G-WRM to a smartphone for 1, 3, and 24 hours, respectively, with each condition repeating for three times.

Data collection and analysis

The data collected from the G-WRM included gyroscope signals and the number of reed switches that were triggered at a sampling rate of 64 Hz (15.62 millisecond). An Android smartphone was used to wirelessly collect data from the G-WRM for all trials except the battery life test at the standalone SD card mode. The angular velocities detected by the G-WRM's gyroscope were used to calculate the speeds and distances traveled. The chuck rotating speeds of the CNC lathe were used as the criterion measure during the CNC lathe test. The roller speeds of the double drum were used as the criterion measure during the double-drum test. The

measured distances using a tape measure and using the SmartWheel and VICON system were used as the criterion measure during the wheelchair propulsion test. The track length was used as the criterion measure during the handcycle test. The data analysis software was written in MATLAB® (version 7.12 R2012b, The Mathworks Inc., Natick, MA, USA) and used to process and analyze data from the G-WRM and criterion measures.

The comparisons between the estimated measures from the G-WRM (i.e. angular velocities and speeds and distances traveled) and criterion measures were performed by calculating the absolute difference, mean difference, percentage errors and standard error of measurement for each trial. Intraclass correlation coefficients (ICC (3,1)) for single measure using two-way mixed model with consistency were used to assess the agreement between the estimated and criterion measures. ICC values of 0.9 or greater are deemed excellent if the lower bounds are greater than or equal to 0.75.¹⁸ The Bland–Altman plots were also used to assess the agreement between the criterion measures and the G-WRMs.¹⁹ The points on the Bland–Altman plots represent the mean (*x*-axis) and the difference (*y*-axis) of the criterion measures and the G-WRMs. All statistical analysis was performed using SPSS software (version 15.0, SPSS Inc., Chicago, IL, USA), with the statistical significance at an alpha level of 0.05.

Results

Table 2 shows the results from the CNC lathe test and the double-drum test. Table 3 shows the results from

Table 2 The estimation errors of G-WRMs for bench tests with CNC lathe for angular velocity and double drum for linear speed

Tests	Absolute error in percentage (%)			Mean percentage error (SD)			Standard error of measurement		
	G-WRM 1	G-WRM 2	G-WRM 3	G-WRM 1	G-WRM 2	G-WRM 3	G-WRM 1	G-WRM 2	G-WRM 3
CNC lathe									
Forward and backward at 40 rpm	0.12	0.03	0.64	0.12 (0.05)	0.00 (0.04)	0.00 (0.70)	0.02	0.02	0.29
Forward and backward at 60 rpm	0.15	0.40	0.40	0.15 (0.08)	0.01 (0.44)	0.01 (0.43)	0.03	0.18	0.18
Forward and backward at 80 rpm	0.17	0.53	0.34	0.17 (0.07)	0.06 (0.58)	0.03 (0.38)	0.03	0.24	0.15
Double drum									
Forward and backward without slats	0.66	0.73	1.22	0.27 (0.91)	−0.36 (0.78)	−0.91 (0.90)	0.41	0.35	0.37
Forward and backward with slats	2.11	1.88	2.19	−2.11 (0.56)	−1.88 (0.58)	−2.19 (1.03)	0.19	0.22	0.52

Table 3 The estimation errors of G-WRMs for various wheelchair propulsion tasks

Propulsion test	Absolute error in percentage			Mean percentage error (SD)			Standard error of measurement		
	G-WRM 1	G-WRM 2	G-WRM 3	G-WRM 1	G-WRM 2	G-WRM 3	G-WRM 1	G-WRM 2	G-WRM 3
Forward (10 m)	0.49	0.59	0.61	-0.49 (0.15)	0.16 (0.82)	-0.52 (0.81)	0.05	0.27	0.27
Forward (15 m)	0.63	0.88	0.60	-0.46 (0.65)	-0.05 (1.19)	0.33 (0.76)	0.20	0.38	0.24
Forward (20 m)	0.18	0.58	0.65	-0.15 (0.17)	-0.34 (0.53)	0.34 (0.69)	0.05	0.17	0.22
Backward (10 m)	0.44	0.94	0.60	0.44 (0.21)	-0.94 (0.16)	-0.60 (0.19)	0.07	0.06	0.07
Forward on a ramp	0.42	0.82	0.53	-0.39 (0.34)	-0.82 (0.39)	-0.06 (0.68)	0.08	0.09	0.16
Forward with camber (10 m)	0.39	1.38	0.85	0.39 (0.20)	1.38 (0.52)	0.85 (0.18)	0.08	0.21	0.07
Forward with camber (15 m)	0.74	0.77	1.16	0.74 (0.24)	-0.77 (0.23)	1.16 (0.19)	0.09	0.08	0.07
Forward with camber (20 m)	0.53	0.78	1.30	0.53 (0.33)	-0.78 (0.15)	1.30 (0.28)	0.13	0.06	0.12
Forward with SmartWheel (18 m)	0.17	0.65	0.68	0.09 (0.24)	0.65 (0.15)	-0.53 (0.47)	0.09	0.06	0.18
Forward with VICON (18 m)	0.48	0.46	0.82	-0.46 (0.84)	0.13 (0.77)	-0.80 (1.05)	0.19	0.17	0.24

the wheelchair propulsion test. The average absolute percentage errors for distances traveled combining the three G-WRMs for the forward (10, 15, and 20 m) and backward propulsion trials (10 m) was 0.58% with a camber of 2.5°, and 0.88% with a camber of 15.5°. This indicates that a camber of 15.5° did not significantly affect the G-WRMs distance estimation. The ICC (3,1) values for the three G-WRMs for the forward propulsion trails (10, 15, and 20 m) with

cambers of 2.5° and 15.5° varied from 0.999 to 1.000 (lower bound: 0.997–1.000 and upper bound: 1.000–1.000). The Bland–Altman plots were also used to assess the agreements between the G-WRMs and the criterion measures during the wheelchair propulsion test (Figs 6 and 7). The distances estimated by G-WRM 1, G-WRM 2, and G-WRM 3 for the handcycling test were 7.17, 7.24, and 7.31 km which correspond to error percentages of 1.06, 0.04, and -0.88%,

Figure 6 Bland–Altman plot of distances measured using tape measure versus distances estimated from the G-WRMs during wheelchair propulsion trials for 10, 15 and 20 m distances on a flat surface.

Figure 7 Bland–Altman plot of distances estimated using VICON versus distances estimated from the G-WRMs during wheelchair propulsion trials for a distance of 18 m on a flat surface.

respectively, compared to the track distance of 7.24 km (805 m per lap). The securement of G-WRM 1 to the inner wheel with respect to the center of the handcycling track may have contributed to slightly higher underestimation of the distance traveled in the trial. The results indicate that the G-WRMs can accurately measure angular velocities and distances for regular wheelchair propulsion and handcycling with an accuracy of greater than 95%.

The G-WRM's battery life test in wireless mode indicated that the G-WRMs were able to collect and transmit data at a frequency of 64 Hz and 1 Hz for an average duration of 27 hours and 21 minutes, and 35 hours and 38 minutes, respectively. The G-WRM's battery life tests in standalone SD card mode data indicated that the G-WRMs were able to collect data continuously at 64 Hz and store the data in the SD card at 1 Hz for 139 hours and 54 minutes. The wireless data transmission test indicated that the average data loss rates for data sampled and transmitted at 64 Hz from the G-WRMs to a smartphone for durations of 1, 3 and 24 hours were 0.3, 0.3, and 0.1%, respectively.

Discussion

An accurate wheel rotation monitor for wheelchair users can be an important clinical and consumer tool for tracking activity levels of this population. The activity

information could also help inform wheelchair maintenance, justify wheelchair prescription, and monitor outcomes for clinical interventions. To address this need, we have utilized advancements in miniature sensor technology to develop a compact and easy-to-use wheel rotation monitor to track mobility-related variables such as linear speeds and distances traveled by wheelchair users. In addition, the ability of the G-WRM to provide the mobility parameters to consumers in real-time through smartphone applications opens up a wide variety of mobile health tracking possibilities ranging from community-based PA interventions by clinicians to goal settings by individuals themselves to improve their health and PA behavior.

The results from this study indicate that the G-WRMs can accurately measure angular velocities and estimate speeds and distances traveled by wheelchair users over a spectrum of activities from everyday wheelchair propulsion to wheelchair sports such as handcycling. The absolute and mean percentage errors are lower than 3% for all the tests. While the absolute percentage error provides a single measure of each of the G-WRMs' performance, the average error with standard deviation provides the tendency of the G-WRMs to over- or under-estimate for various trials. The higher percentage error for estimating linear speed during the double-drum test with slats was due to the

wheelchair regularly bouncing which may be associated with slightly higher speeds. Multiple criterion measures used during the tests allowed us to assess both the engineering validity and real-world performance of G-WRMs during wheelchair-related activities. For example, the advantage of using SmartWheel and VICON measurement systems is that they track the distance traveled by the wheelchair user irrespective of whether the user is traversing in a straight line. In addition, the high ICC values indicate a strong agreement between the estimated measures by G-WRMs with criterion measures. The Bland–Altman plots (Figs 6 and 7) showed that the mean differences were close to zero and more than 95% of the values lie within $\text{mean} \pm 2\text{SD}$, indicating excellent agreement between the G-WRMs and criterion measures. We also found that it is important to calibrate each of the G-WRMs to accurately estimate angular velocities as there can be slight variations between the gyroscope sensors. Furthermore, the battery tests indicate that the G-WRM can be used to continuously collect data for a full day while transmitting the information to a smart phone and for at least five continuous days while saving the data on a SD card. The Bluetooth tests indicate that the G-WRM can transmit data continuously with minimal data loss.

Comparing the results of this study with Coulter *et al.*'s study, we find that the average absolute error for all tasks (0.59%) and the ICC values for activPAL in Coulter *et al.*'s study are similar to our results, indicating that the G-WRM is a comparable device to track everyday mobility.⁴ On similar lines, the performance of the G-WRM in estimating distances traveled is close to the results of Sonenblum *et al.*³ who use an accelerometer-based device to track wheelchair movement. However, both studies only tested their devices with regular wheelchair propulsion.^{3,4} The utility of accelerometer-based devices in monitoring wheelchair sport activities is unknown. In our study, we have developed and evaluated G-WRM that can be used across the range of wheelchair related activities from propulsion to handcycling. In addition, the use of a gyroscope sensor instead of an accelerometer allows us to directly obtain angular velocity of the wheelchair's wheel as compared to translating the acceleration values to rotation angles for calculating wheel rotations. This process of using angular velocities directly to estimate linear speeds and distances traveled reduces computational complexity, which allows us to provide wheelchair users with real-time feedback through smartphone applications.

One of the limitations of the G-WRM is that the device in itself may not be able to distinguish between self-propulsion and being pushed by a caretaker.

However, the G-WRM can be used in conjunction with wearable accelerometers to track upper arm-movement to distinguish self-propulsion and external pushing.²⁰ Another limitation of this study is that the G-WRM was evaluated by only two test participants instead of a group of wheelchair users. In addition, most of the data collected and analyzed from the G-WRMs were collected at 64 Hz which could be reduced for many real-world clinical applications. The G-WRM mentioned here has the capacity to be used independently or in conjunction with other motion and physiological-based wearable devices that wirelessly send data via Bluetooth to detect wheelchair users' activity type and context in community settings. Future improvements in G-WRM will involve optimizing the sampling rate of the gyroscope based on the speeds detected during various types of wheelchair-related activities and utilizing the passive reed switches to trigger data collection from the gyroscope only during active wheelchair use to conserve and extend the battery life. We are also working on combining the G-WRM and an upper arm worn accelerometer to estimate energy expenditure of wheelchair users. We plan to evaluate the usability of the G-WRM and the smartphone application with wheelchair users. Furthermore, we are currently in the process of identifying small businesses that are interested in collaborating with the Human Engineering Research Laboratories to commercialize the G-WRMs and make this technology available to multiple stakeholders including researchers, clinicians, and consumers.

Conclusions

To our knowledge, this is the first study to develop and evaluate a gyroscope based wheel rotation monitor to estimate speeds and distances traveled by wheelchair users. The G-WRM is a versatile device that can be used to estimate speeds and distances over a spectrum of wheelchair-related PAs from regular wheelchair propulsion to wheelchair sports such as handcycling.

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