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ORIGINAL ARTICLE

Accelerometer output and its association with energy expenditure during manual wheelchair propulsion

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Study design: This is an experimental design.
Objectives: This study examined the association between rates of energy expenditure (that is, oxygen consumption (VO_2)) and accelerometer counts (that is, vector magnitude (VM)) across a range of speeds during manual wheelchair propulsion on a motor-driven treadmill. Such an association allows for the generation of cutoff points for quantifying the time spent in moderate-to-vigorous physical activity (MVPA) during manual wheelchair propulsion.
Setting: The study was conducted in the University Laboratory.
Methods: Twenty-four manual wheelchair users completed a 6-min period of seated rest and three 6-min periods of manual wheelchair propulsion on a motor-driven wheelchair treadmill. The 6-min periods of wheelchair propulsion corresponded with three treadmill speeds (1.5, 3.0 and 4.5 mph) that elicited a range of physical activity intensities. Participants wore a portable metabolic unit and accelerometers on both wrists. Primary outcome measures included steady-state VO_2 and VM, and the strength of association between VO_2 and VM was based on the multiple correlation and squared multiple correlation coefficients from linear regression analyses.
Results: Strong linear associations were established between VO_2 and VM for the left ($R=0.93\pm0.44$; $R^2=0.87\pm0.19$), right ($R=0.95\pm0.37$; $R^2=0.90\pm0.14$) and combined ($R=0.94\pm0.38$; $R^2=0.88\pm0.15$) accelerometers. The linear relationship between VO_2 and VM for the left, right and combined wrists yielded cutoff points for MVPA of 3659 ± 1302, 3630 ± 1403 and 3644 ± 1339 counts min^{-1}, respectively.
Conclusion: We provide cutoff points based on the linear association between energy expenditure and accelerometer counts for estimating time spent in MVPA during manual wheelchair propulsion using wrist-worn accelerometry. The similarity across wrist location permits flexibility in selecting a location for wrist accelerometry placement.
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INTRODUCTION

There is clear recognition regarding the health benefits of physical activity among wheelchair users.[1–3] This has prompted investigations of determinants that can become targets of interventions for promoting physical activity participation among wheelchair users. Such efforts are directed toward increasing time spent in moderate-to-vigorous physical activity (MVPA) among wheelchair users (that is, public health guidelines for health benefits of 150 min per week of MVPA[4]). The time spent in MVPA could include participation in structured exercise training within a clinical setting or free-living physical activity such as everyday wheelchair propulsion.

The study of physical activity in wheelchair users requires objective measures that can be linked with the aforementioned public health recommendations for physical activity. This may best be accomplished using accelerometers. Accelerometers worn around the wrist measure upper extremity movement during manual wheelchair propulsion.[5] Such accelerometers monitor acceleration of movement and provide information on movement intensity during physical activity as activity counts. Wrist-worn accelerometers have been deemed an accurate and practical anatomical location to provide a representation of the wearer's physical activity.[1] Accelerometers provide representation of body movement and may be more representative of physical activity than other measures such as wheel revolutions that represent wheelchair movement only. Arm dominance or unilateral weakness (that is, hemiparesis) may affect wheelchair propulsion, and these factors may be important when considering placement of wrist-worn accelerometers. To date, it has not been clarified whether one accelerometer is sufficient, regardless of wrist location, or whether accelerometers should be worn on both wrists for improved monitoring of physical activity. Triaxial accelerometers, in particular, provide activity counts over three axes during movement and can be summarized into a vector magnitude (VM) that proportionally reflects the total net external acceleration generated during movement. The VM further can be associated with energy expenditure during physical activity.[6]

Researchers have established an association between waist-worn accelerometer output and energy expenditure based on indirect calorimetry during ambulatory physical activity on a motor-driven treadmill.[7–11] The protocols have involved measuring accelerometer metrics and energy expenditure during rest and across a range of speeds that mimic a range of physical activity from light to vigorous;

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this has resulted in cutoff points for better understanding and quantifying time spent in MVPA among the general population and in ambulatory individuals with disabilities. The cutoff points are derived from the generation of corresponding data points for both energy expenditure and accelerometer output during rest, and a range of speeds for generation of a linear relationship per person that can then yield an overall association and cutoff points. This is a standard approach that we are applying for this first time in wheelchair users. Cutoff points for MVPA derived from walking on a motorized treadmill have been applied in population-based studies of free-living physical activity levels, studies of determinants of everyday physical activity and physical activity interventions. We therefore see great value in establishing cutoff points for MVPA in wheelchair users using a similar protocol.

Researchers have examined the relationship between single wrist-worn uniaxial[2] and triaxial[1] accelerometer output and energy expenditure in samples of wheelchair users using overground methodology. One study[1] requested that participants self-propel around an outdoor athletic track. Speed was manipulated by participants using real-time speed feedback with a global positioning system cycle computer placed on the participant's lap. The other study[2] had participants wheel around a rectangular indoor course, and speed was manipulated by asking participants to maintain a 'slower than normal', 'normal' or 'faster than normal' speed. Such attempts to manipulate speed may be improved through an external researcher controlled preparation, for example, using a wheelchair motor-driven treadmill that allows for accurate speed determination. Such treadmill methodology is an accepted surrogate to overground wheelchair propulsion.[12] This further mimics initial and robust efforts for deriving cutoff points from ambulatory persons using treadmill preparations.[7–11]

To date, researchers have not examined the association between accelerometer output and energy expenditure using a motor-driven wheelchair treadmill. Researchers further have not established cutoff points for accelerometer output as an approach for measuring MVPA among wheelchair users. Such cutoff points would provide a biological meaning for interpreting accelerometer output based on the association with energy expenditure and offer greater value than total activity counts when quantifying physical activity behavior. The existing cutoff points for ambulatory individuals obviously are not applicable among wheelchair users, and this emphasizes the importance of establishing cutoff points for measuring time spent in MVPA during wheelchair propulsion as an important advancement for quantifying free-living physical activity behavior. Researchers have not clearly established the rationale for wearing accelerometers on one wrist only as a means for establishing physical activity during wheelchair propulsion; doing so may offer greater flexibility in data collection and highlight the influence of asymmetry in arm dominance.

This study examined the association between rates of energy expenditure (that is, oxygen consumption (VO_2)) and accelerometer counts (that is, VM) across a range of speeds during manual wheelchair propulsion on a motor-driven treadmill. On the basis of the association, we generated cutoff points for quantifying time spent in MVPA during manual wheelchair propulsion. Our study mimics previous protocol wherein treadmill walking was performed as a representation of real-world walking.[7–11] We hypothesized that there would be an increase in accelerometer counts and energy expenditure with increased propulsion speed, and that a strong linear relationship would exist between rates of accelerometer counts and energy expenditure during wheelchair propulsion. We further evaluated the effect of anatomical positioning (that is, comparison in bilateral wrist-worn accelerometers) of wrist-worn accelerometers on metrics for the regression analysis (that is, R, R^2, slope and intercept). Such data will provide rationale on the use of unilateral or bilateral wrist-worn accelerometers in monitoring wheelchair-based physical activity.

MATERIALS AND METHODS

Sample

The protocol was approved by a university institutional review board, and all participants provided written informed consent before participation in the study. We recruited participants through direct contact with wheelchair users on a university campus or who had previously taken part in our research. We further placed flyers within a local veterans support center and a residential association for persons with physical disabilities. Inclusion criteria were (a) manual wheelchair user (that is, as a primary means of mobility to combine for $\geqslant$80% ambulation or $\geqslant$40 h per week, (b) aged 18-64 years, (c) having the visual ability to read 14-point font and (d) being willing and able to wear the accelerometers and oxygen analysis system while undertaking manual wheelchair propulsion. We screened 28 wheelchair users; two persons did not meet the inclusion criteria and one person cancelled the testing session after screening. One participant with multiple sclerosis had severe upper limb weakness and was unable to complete the protocol, and therefore was not included in our analysis. We included a final sample of 24 manual wheelchair users.

Primary measurements

Energy expenditure. Energy expenditure was measured as oxygen consumption (VO_2) using a portable metabolic unit (K4b2, Cosmed, Rome, Italy).[13] The K4b2 unit was prepared according to the standard procedure.[11] The K4b2 unit was placed in the standard shoulder harness with the K4b2 located on the sternum and the battery located on the upper back. This standard harness allows for minimal interference during wheelchair propulsion. The data were collected breath-by-breath and we retrieved the data as 30-s averages for further processing in Microsoft Excel. The analyses involved steady-state VO_2 in $ml\,kg^{-1}min^{-1}$ by averaging the 30-s VO_2 values over the final 3 min of the 6-min periods of rest and three periods of wheelchair propulsion on the treadmill.

Accelerometer count. Accelerometer counts were measured as VM by wrist-worn triaxial ActiGraph accelerometers (GT3X, Health One Technology, Pensacola, FL, USA).[14] The GT3X is designed to measure and record time-varying acceleration ranging in magnitude from 0.05 to 2.5 G. The acceleration signal is digitized by a 12-bit analog-to-digital converter, at a sampling rate of thirty times per second (30 Hz). The GT3X accelerometers were prepared according to standard procedures,[11] and one GT3X accelerometer was worn per wrist, placed posterior to the radial and ulnar styloid process. Accelerometers were worn on both wrists to monitor possible asymmetry in wrist acceleration during propulsion, and such methodology is necessary to make recommendations as to whether wrist accelerometers are worn on one or both wrists. The accelerometer signal was processed into 30-s epochs, and imported into Microsoft Excel for further processing. Steady-state data for VM were averaged over the same 30-s intervals as per VO_2.

Protocol. On the day of testing, participants completed a demographic questionnaire and the physical activity scale for individuals with physical disabilities (PASIPD).[15] The PASIPD provides an estimate of physical activity that is calculated from information on leisure, household and occupational physical activity over the previous 7 days. We measured the participants weight using a wheelchair scale (LW Measurements, Santa Rosa, CA, USA) and estimated height based on tibia length.[16] Participants were initially instructed on the wheelchair propulsion protocol. Participants were provided with a 2-min period of acclimatization of manual wheelchair propulsion on the treadmill, followed by a 10-min period of rest. The testing protocol itself involved participants sitting quietly for 6 min to establish estimates of resting VO_2 and VM. The participants then undertook up to three, 6-min periods of manual wheelchair propulsion on a motor-driven wheelchair treadmill (Max Mobility, Antioch, TN, USA) with 10-min periods of full recovery between the wheelchair propulsion trials. The three wheelchair propulsion speeds were 1.5, 3.0 and 4.5 mph. The order of speeds was randomized across testing.

Data processing and analysis. We entered the steady-state accelerometer and metabolic data (that is, average of the final 3 min of rest and three periods of wheelchair propulsion) per participant into Microsoft Excel. This allowed for estimating the multiple correlation coefficient (R), squared multiple correlation coefficient (R^2), intercept, slope and cutoff point for MVPA (that is, $\geqslant 3$ metabolic equivalents or 10.5 ml kg^{-1} min^{-1}) based on the linear relationship between changes in VO_2 and VM per participant. The parameters for R and R^2 permitted an assessment of the strength of association between steady-state accelerometer and metabolic data. The intercept and slope described the nature of the association between steady-state accelerometer and metabolic data, and these parameters yielded the cutoff point for MVPA.

Data were analyzed using PASW Statistics 22 (SPSS Inc., Chicago, IL, USA). Descriptive statistics are reported as mean and s.d. To confirm the speed manipulation and its influence on outcomes, we examined rates of energy expenditure and left and right accelerometer outputs over the three, 6-min wheelchair propulsion trials using two-way, speed (1.5, 3.0 and 4.5 mph) by time (12 and 30-s increments) within-subjects analysis of variance (ANOVA). We examined differences in steady-state energy expenditure and left and right accelerometer output across speed (1.5, 3.0 and 4.5 mph) using one-way within-subjects ANOVA as a further confirmation of the speed manipulation and its influence on outcomes that are included in the main analysis. We examined correlations between metrics for the regression analysis (that is, R, R^2, slope and intercept) from the left- and right-wrist accelerometer data using Pearson's product–moment correlations.

RESULTS

Descriptive statistics

The sample consisted of 24 wheelchair users (15 males) with a mean age of 32.5 years (s.d. = 11.6, median = 28, range = 19–55). The conditions responsible for wheelchair use were spinal cord injury ($n = 10$), spina bifida ($n = 5$), multiple sclerosis (MS) ($n = 4$), amputation ($n = 2$), congenital bone disorder ($n = 2$), cerebral palsy ($n = 1$) and demyelinating disease (non-MS; $n = 1$). The mean score for the PASIPD was 36.1 ± 15.9, indicating that the sample was physically active.[15]

Wheelchair treadmill protocol

Twenty-two participants completed the three 6-min periods of wheelchair propulsion. Two participants with MS were unable to complete the final period of wheelchair propulsion (that is, one for the 3.0 mph trial and one for the 4.5 mph trial).

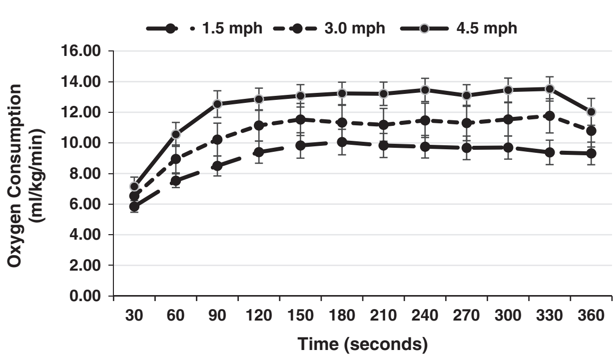

Figure 1 Oxygen consumption (ml kg^{-1} min^{-1}) over the three, 6-min periods of wheelchair propulsion at 1.5, 3.0 and 4.5 mph, indicating a similar pattern of initial change followed by steady-state kinetics.

Manipulation check on energy expenditure and accelerometer output

The 30-s energy expenditure data and accelerometer data over the three 6-min trials are represented in Figures 1 and 2, respectively. The two-way ANOVA indicated that there was no significant speed by time interaction on energy expenditure ($\eta^2 = 0.06$, F = 1.34, $P = 0.12$). The two-way ANOVAs indicated that there were no significant speed by time interactions on VM data (left; $\eta^2 = 0.04$, F = 1.01, $P = 0.45$, and right; $\eta^2 = 0.03$, F = 0.60, $P = 0.93$). This confirmed that the rates of change in energy expenditure data and accelerometer data over time did not differ among speeds providing an important check on the steady-state kinematics and parameters.

The steady-state energy expenditure and accelerometer data (that is, average of the final 3 min) for the four trials (that is, rest, 1.5, 3.0 and 4.5 mph) are provided in Table 1; these data provided important information on the effect of speed on energy expenditure and accelerometer output as a check on the successful manipulation of speed. The one-way ANOVA indicated that speed had a significant and large main effect on energy expenditure ($\eta_p^2 = 0.81$, F = 100.40, $P < 0.001$). Speed had a significant and large main effect on the accelerometer counts (left; $\eta_p^2 = 0.80$, F = 93.26, $P < 0.001$ and right; $\eta_p^2 = 0.79$, F = 87.45, $P < 0.001$).

Association between energy expenditure and accelerometer counts

There was a strong linear association between accelerometer activity counts and energy expenditure across speeds in both the left ($R = 0.93 \pm 0.44$; $R^2 = 0.87 \pm 0.19$) and right ($R = 0.95 \pm 0.37$; $R^2 = 0.90 \pm 0.14$) wrists and overall (that is, combined left and right wrist) ($R = 0.94 \pm 0.38$; $R^2 = 0.88 \pm 0.15$). The linear regression equations for predicting energy expenditure from accelerometer counts were as follows:

left wrist: energy expenditure = 0.0021 (counts min^{-1})+3.14,

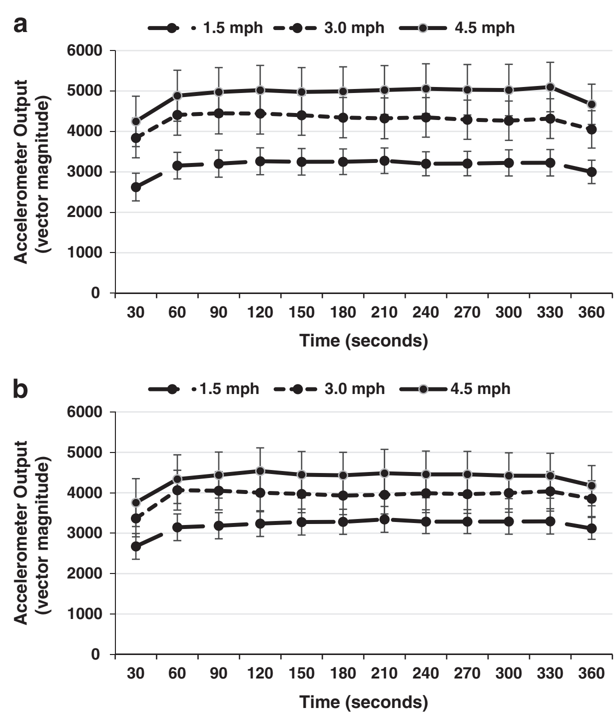

Figure 2 Left-wrist (**a**) and right-wrist (**b**) accelerometer output (vector magnitude) over the three, 6-min periods of wheelchair propulsion at 1.5, 3.0 and 4.5 mph, indicating a similar pattern of acceleration per wrist over the three speeds.

Table 1 Oxygen consumption and accelerometer output for rest and the three speeds of wheelchair treadmill propulsion, indicating the success of the speed manipulation.

Variable	*Rest*	*1.5 mph*	*3.0 mph*	*4.5 mph*	η_p^2 *(F-value)*	P*-value*
Oxygen consumption (VO_2 (ml min $^{-1}$ kg $^{-1}$))	4.1 ± 0.9	8.0 ± 2.1	10.8 ± 3.2	15.6 ± 4.6	0.81 (100.40)	< 0.001
Left accelerometer output (VM)	140.1 ± 154.5	2799.2 ± 1279.1	4284.9 ± 1991.9	5413.7 ± 2538.8	0.80 (93.26)	< 0.001
Right accelerometer output (VM)	154.9 ± 202.8	2800.5 ± 1267.6	4206.0 ± 2055.6	5584.5 ± 2797.9	0.79 (87.45)	< 0.001

Abbreviations: VM, vector magnitude. VO_2, oxygen consumption.

right wrist: energy expenditure = 0.0022 (counts min $^{-1}$)+3.13, and combined wrists: energy expenditure = 0.0022 (counts min $^{-1}$) +3.13.

There were strong correlations between R (r = 0.90, P < 0.01), R^2 (r = 0.91, P < 0.01), equation slope (r = 0.89, P < 0.010) and intercept (r = 0.98, P < 0.01) for the association between accelerometer output and energy expenditure in left and right wrists.

Cutoff points for moderate-to-vigorous physical activity

The association between energy expenditure and accelerometer output across speeds resulted in a cutoff point for MVPA of 3659 ± 1302 counts min^{-1} for the left wrist, and 3630 ± 1403 counts min $^{-1}$ for the right wrist. The summary cutoff point from both left and right wrists for MVPA was 3644 ± 1339.

DISCUSSION

This study examined the association between rates of accelerometer output (VM) and energy expenditure (VO_2) during steady-state treadmill wheelchair propulsion in wheelchair users. This investigation tested the assumption of a strong association between rates of activity counts and energy expenditure in wheelchair users.[1,2] That assumption and resulting evidence facilitated the development of cutoff points for quantifying time spent in MVPA using wrist-worn accelerometers as a means of measuring upper extremity movement during manual wheelchair propulsion as representation of physical activity that could be accumulated during exercise or daily life. The primary results indicated a strong, linear association between VO_2 and VM in wheelchair users; the effect was consistent across both wrists. This suggests that wrist-worn accelerometer output reflects energy expenditure during wheelchair propulsion.[6] Results further yielded cutoff points for quantifying MVPA in wheelchair users. Such cutoff points will permit quantification of time spent in MVPA using wrist-worn accelerometry among wheelchair users.

Washburn and Copay[2] established a moderate correlation between energy expenditure and left-wrist (R = 0.52) and right-wrist (R = 0.66) uniaxial accelerometer output in 21 wheelchair users. Nightingale *et al.*[1] established a strong linear relationship between energy expenditure and output from right-wrist (R = 0.93) triaxial accelerometers in 15 wheelchair users. Our protocol was undertaken in a controlled environment (that is, wheelchair propulsion at precise speeds controlled by a wheelchair motor-driven treadmill) that yielded high internal validity, but it might not have high external validity. The results from our analyses support the internal validity of our protocol, as a clear distinction in VO_2 and VM was present across speeds. We further included current triaxial accelerometers worn on both wrists in a comparative sample of full-time wheelchair users providing complete data as to upper limb physical activity during wheelchair propulsion.

We provide linear regression equations for wrist-worn accelerometry and energy expenditure, and believe that researchers and clinicians should use the values reported herein to predict energy expenditure during physical activity in wheelchair users. We further provide the first set of cutoff points for quantifying time spent in MVPA based on the rate of accelerometer activity counts per minute among wheelchair users. To our knowledge, such data are only available in ambulatory individuals without[8,9] or with[10,11] mobility disability. Our data provide cutoff points for computing time spent in MVPA during general wheelchair propulsion and have real-world importance for studies of physical activity and physical activity interventions in wheelchair users. We report that there were strong correlations between the metrics (that is, regression coefficients and cutoff points) from the left- and right-wrist accelerometers. This suggests that either wrist could provide accurate energy expenditure and that the more functional wrist could be targeted in cases of a more hemiparetic presentation. However, further study is required in these medical conditions.

The study has a number of strengths over past similar studies including the variety of medical conditions represented in our sample. Our protocol offers high precision via the use of triaxial accelerometers worn on both wrists and the use of motor-driven treadmill technology to accurately control speed. Our study further is the first to compare triaxial accelerometers worn on both wrists during wheelchair propulsion. Some important limitations should be considered when interpreting the results. Our sample was representative of a physically active wheelchair population. Our sample included participants who had some degree of upper extremity dysfunction or weakness; however, all participants had enough upper limb control to manually push a wheelchair. These requirements were necessary given the methodology constraints (for example, the ability to maintain constant wheelchair propulsion over 6 min at 4.5 mph), but they limit the applicability to those with upper extremity disability.

Collectively, our findings of a strong association between energy expenditure and accelerometer output that resulted in cutoff points for quantifying MVPA during wheelchair propulsion indicate that wrist-worn accelerometers could be useful for measuring physical activity in wheelchair users. This may permit better characterization of physical activity levels and associations between physical activity and health outcomes in wheelchair users. This may further permit improved examination of determinants of physical activity and quantification of behavior intervention effects. Future research should consider these results when examining physical activity using accelerometers in wheelchair users.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

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