Research Article

Exercise testing protocol using a roller system for manual wheelchair users with spinal cord injury

Kerri A. Morgan¹, Kelly L. Taylor¹, Susan M. Tucker¹, W. Todd Cade², Joseph W. Klaesner ²

¹Program in Occupational Therapy, Washington University School of Medicine, St. Louis, Missouri, USA, ²Program in Physical Therapy, Washington University School of Medicine, St. Louis, Missouri, USA

Objective: Determine the validity and reliability of an exercise testing protocol to evaluate cardiorespiratory measures in manual wheelchair users (MWUs) with spinal cord injury (SCI) using a roller-based (RS) wheelchair system.

Design: Repeated measures within-subject design.

Setting: Community-based research laboratory.

Participants: Ten adults with SCI requiring the use of a manual wheelchair.

Interventions: Not applicable.

Outcome measures: Cardiorespiratory measures (peak oxygen consumption [$\text{VO}_{2\text{peak}}$], respiratory exchange ratio [RER], pulmonary ventilation [VE], energy expenditure [EE], heart rate [HR], accumulated kilocalories [AcKcal]) and perceived exertion (RPE) were measured during three separate maximal exercise tests using an arm crank ergometer (ACE) and an RS.

Results: At maximal exertion, there were no significant differences in variables between groups, with moderate-to-strong correlations ($P < 0.05$, $r = 0.79\text{--}0.90$) for VO_2 , HR, RPE, AcKcal, and rate of EE between RS and ACE trials. Significant moderate-to-strong correlations existed between RS trials for VO_2 , AcKcal, rate of EE, and peak power output ($P < 0.01$, $r = 0.77\text{--}0.97$).

Conclusions: $\text{VO}_{2\text{peak}}$ was highly correlated between ACE and RS trials and between the two RS trials, indicating the RS protocol to be reliable and valid for MWUs with SCI. Differences in perceived exertion and efficiency at submaximal workloads and maximal pulmonary ventilation at peak workloads indicated potential advantages to using the RS.

Keywords: Spinal cord injury, manual wheelchair, exercise testing, cardiorespiratory fitness, wheelchair roller system

Introduction

Approximately 282,000 people in the United States are living with spinal cord injury (SCI).¹ Due to the decreased physical capacity associated with their disabilities,² persons with SCI are at a greater risk for major health conditions and mortality from chronic diseases directly associated with physical inactivity, including cardiovascular disease, diabetes, obesity, and depression.^{3–7} Fewer than 25% of adults with disabilities engage in

physical activity sufficient to gain activity-related health benefits, while those with SCI report the lowest levels of physical activity.^{8–10} Poor cardiovascular health commonly experienced by persons with SCI suggests a great need for increased physical activity and fitness in this population. However, there is a lack of evidence regarding the optimal exercise assessment and training protocols for cardiorespiratory fitness for adults with SCI.

The current gold standard for assessing cardiovascular fitness is measuring the peak volume of oxygen consumption ($\text{VO}_{2\text{peak}}$) during a graded exercise test.^{11–13} For adults with SCI, $\text{VO}_{2\text{peak}}$ is most commonly evaluated using an arm crank ergometer (ACE).^{7,14–18} While limited, norm-reference values for $\text{VO}_{2\text{peak}}$ in

Correspondence to: Kerri A. Morgan, PhD, OTR/L, ATP, Program in Occupational Therapy, Washington University School of Medicine, 4444 Forest Park Avenue, Campus Box 8505, St. Louis, MO 63108-2212, USA. Email: morgank@wustl.edu or morgank@wusm.wustl.edu

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adults with SCI are based on studies conducted using ACEs.^{15,19} Although these devices have been shown to produce health-related changes in adults with SCI, ACEs have limitations. The most common type of mobility device used among persons with SCI is a manual wheelchair for everyday mobility.¹ The operation of an ACE employs an unfamiliar and non-functional movement pattern not typically used in daily life activities for this population. Impairments in trunk control and hand strength for manual wheelchair users (MWUs) with SCI are often difficult to accommodate while using an ACE. These limitations of ACEs, commonly used for measuring an MWU with SCI's $\text{VO}_{2\text{peak}}$ during incremental exercise testing, typically result in a non-functional movement pattern, potentially influencing the MWU with SCI's ability to achieve maximal exertion.

Wheelchair propulsion is the primary functional movement pattern for MWUs with SCI and is associated with an increased cardiorespiratory response.¹² Researchers and clinicians commonly conduct manual wheelchair research and training using a wheelchair propulsion simulation device,^{20–24} eliminating the problem of limited lab or clinic space and simplifies data collection methods by placing the participant and wheelchair in a relatively stationary location. Roller systems (RS) are commonly used wheelchair propulsion simulation devices that consist of one or two parallel rollers and a platform to secure the front wheelchair casters.^{23–26} Typically, RS are able to manipulate resistance, simulating various terrain types,, with some recent devices having the ability to manipulate slope, cross-slope, and camber.^{23,24} The customizable nature of the RS promotes functional movement patterns, possibly providing a superior testing setup. The purpose of this study was to determine the validity and reliability of an exercise testing protocol to evaluate cardiorespiratory fitness in MWUs with SCI using a roller system. This study also investigates the work economy and mechanical efficiency of MWUs with SCI at a submaximal workload during each testing mode.

Methods

Study design

A repeated measures within-subject design was used.

Participants

MWUs with SCI were enrolled in the study (Table 1). Potential participants were recruited through the local independent living center, and word of mouth. Participants were eligible if they were between 18 and 60 years of age, a traumatic or non-traumatic SCI diagnosis, and used a manual wheelchair for $\geq 75\%$ of daily mobility. Participants were excluded from the study if

Table 1 Participant characteristics.

Variables	n (10)	Percentage	Mean $\pm$ SD
Sex			
Male	10	100	
Weight (kg)			75.7 $\pm$ 11.6
Age (years)			33 $\pm$ 19.6
Level of Injury			
C5-6	1	10	
C6-7	6	60	
T4-6	1	10	
T8-11	2	20	
ASIA Level			
A	2	20	
B	6	60	
C	2	20	
Activity Level			
Light	0	0	
Moderate	6	60	
Vigorous	4	40	
Frequency (days/week)			4.1 $\pm$ 1.7
Duration (min/week)			378.3 $\pm$ 142.2
Sport participation	7	70%	

ASIA, American Spinal Cord Injury Association Impairment Scale.

they manoeuvred their wheelchair with their lower extremities or with only one arm, history of cardiorespiratory complications within the previous year, acute upper extremity injury, and/or pain rated 6/10 or higher. The study was approved by the Washington University Human Research Protection Office. Prior to exercise tests, all participants obtained approval and signed-release from a physician and provided informed consent.

Procedures

Participants performed three incremental maximal exercise tests: two on an RS and one on an ACE. Testing sessions were performed on three separate days; at least 48 hours apart. The order of the three exercise tests was randomized for each participant to minimize order and carry-over effects.

Prior to testing, all participants were asked to refrain from any strenuous physical activity for 24 hours. Before initiating the exercise tests, participants remained stationary for 10 minutes to measure resting heart rate (HR) and blood pressure (BP). Pain level and weight were also measured prior to each exercise test. After participants were securely positioned in their everyday manual wheelchair on the testing device, a 3-minute standardized warm-up commenced, followed by a maximal exercise test using a continuous stepwise protocol with workload increases in 1-minute intervals until exhaustion. All maximal exercise tests were immediately followed by an active cool-down period lasting at least 3 minutes. Standard indications for test termination were used ($\text{RER} \geq 1.1$, $\text{RPE} \geq 17$).²⁷ Participants were closely monitored for adverse effects during testing; no

participants experienced adverse events. Participants received a printout of their results at the completion of each test. All tests were performed at room temperature (20°–24°C) with 32%–46% humidity.

Roller system test

The RS exercise test was performed on a wheelchair dynamometer known as the WheelMill System (WMS), a ramp-accessed, roller-based, computer-controlled system that can simulate various resistant surfaces and slopes in a laboratory or clinical setting and allows a person to use his or her own wheelchair while propelling on the device (Figure 1).^{23,24} The WMS allows for manipulation of resistance, slope, cross-slope, and camber²⁴ and is able to accommodate a variety of sizes and types of wheelchairs.

The test protocol for the WMS included a 3-minute warm-up period followed by assessment of participants' maximum velocity for 10 seconds. During the individualized ramp protocol of the exercise test, participants maintained 70% of their maximum velocity while resistance²⁴ was increased stepwise in 1-minute intervals, until exhaustion.

Arm crank ergometer test

The ACE exercise test was performed on a SCIFIT PRO1000 (Life Fitness, Tulsa, OK, US). Participants

remained in their manual wheelchairs on a secured platform for the duration of testing (Figure 2). To achieve proper glenohumeral alignment with the ACE, the axes of rotation for the arm cranks were set just below shoulder level, and participants' elbows were slightly flexed at the moment of furthest reach. For participants who were unable to independently grip the ACE handles, Ace bandage wraps were used to secure their hands during the test. The asynchronous ACE testing protocol included a 3-minute warm-up at 6 watts (W) with 60 revolutions per minute (rpm) followed by a standard ACE ramp protocol. All participants initiated the maximal test at 10 W, with incremental increases by 7 W every minute, until exhaustion. Participants were required to maintain 60 rpm throughout the duration of the exercise test.

Outcome measures

Cardiorespiratory measures

During the exercise tests, VO_2 ($\text{L} \cdot \text{min}^{-1}$ and $\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), respiratory exchange ratio (RER), pulmonary ventilation ($\text{L} \cdot \text{min}^{-1}$), and energy expenditure (EE; $\text{Kcal} \cdot \text{min}^{-1}$ and AcKcal) were measured using a standard computer-integrated, open-circuit, breath-by-breath metabolic measurement system (TrueOne 2400, ParvoMedics, Sandy, UT, US). The TrueOne 2400 has been used with both MWUs and

Figure 1 Experimental setup for the RS.

Figure 2 Experimental setup for the ACE.

able-bodied persons and has been shown to be a reliable and valid metabolic measurement system.^{28,29} Gas and volume calibrations were conducted prior to each test. HR was continuously measured during all test stages, including warm-up and cool-down, using a heart rate monitor (H1 Heart Rate Sensor, Polar Electro Inc., Lake Success, NY, US).

Perceived exertion

Participants were asked to rate their perceived exertion using Borg's Rating of Perceived Exertion Scale (RPE; 6–20)³⁰ during the warm-up period, the last 30 seconds of each incremental stage, immediately following completion of the maximal test, and every minute of cool-down.

Data analysis and statistics

The highest VO_2 achieved that met determination criteria ($\text{RER} \geq 1.1$; $\text{RPE} \geq 17$) was averaged over 1 minute and used as criteria for $\text{VO}_{2\text{peak}}$. Data from participants who did not meet both criteria were excluded from analysis. The current study used a within-group design; therefore, all participants were grouped together for data analysis. Validity was demonstrated by comparing the first trial on the RS with the ACE trial. Reliability and reproducibility were demonstrated by comparing both trials on the RS. Resting energy expenditure (REE) was estimated using the Harris-Benedict equation.³¹ Work economy and mechanical efficiency calculations used a constant submaximal workload (30 W) for both RS and ACE tests. Mechanical efficiency (ME), the percentage of energy expended that contributes to exercise,³² was calculated according to the following equation:

$$\text{ME (\%)} = \left[\frac{\text{watt} \times 0.01433}{E - \text{REE}} \right] \times 100 \quad (1)$$

where watt, E, and REE are the submaximal exercise load of 30 W, energy expenditure during exercise ($\text{Kcal} \cdot \text{min}^{-1}$), and resting energy expenditure ($\text{Kcal} \cdot \text{min}^{-1}$), respectively.^{33,34} One caloric equivalent is represented by the figure 0.01433.

Statistical analyses were conducted using the Statistical Package for the Social Science (version 24 SPSS Inc., Chicago, IL, US). Paired sample t-tests were used to compare maximal and submaximal cardiovascular and energetic responses between RS and ACE exercise tests. Inter-class correlations (Pearson's) were used to assess relationships among outcome measures between RS₁ and ACE tests, intra-class correlations (ICC) Model 3,1 were performed to compare reliability of RS trials, and Bland-Altman plots were constructed to illustrate the limits of agreement between primary outcome measures (VO_2 , RER, HR, and RPE) when comparing ACE and RS trials. Values are expressed as mean $\pm$ SD, unless otherwise stated. Two-tailed significance was accepted at $P < 0.05$.

Results

Ten ($n = 10$) participants (Table 1) completed all exercise tests without any adverse events. Due to his inability to maintain 60 rpm beyond 52 W, one participant's ACE test was terminated prior to volitional exhaustion ($\text{RER} < 1.1$; $\text{RPE} < 17$); therefore, his peak ACE data were excluded from statistical analysis. Volitional exhaustion was the reason for testing termination for all other trials and participants. Paired sample t-tests revealed no significant differences in $\text{VO}_{2\text{peak}}$ or peak values of HR, RER, RPE, AcKcal, rate of energy expenditure, and power output between RS and ACE trials (Table 2; Figures 3 and 4). Inter-class correlations between RS_{peak} and ACE_{peak} tests revealed good concurrent validity with significant moderate-to-strong correlations for

Table 2 Peak and submaximal metabolic and energetic values (mean $\pm$ SD) during RS and ACE.

Variables	RS ₁ peak ($n = 10$)	RS ₂ peak ($n = 10$)	ACE peak ($n = 9$)	RS ₁ 30 W ($n = 10$)	ACE 30 W ($n = 10$)
VO_2 ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	17.3 $\pm$ 3.3	18.1 $\pm$ 2.3	15.9 $\pm$ 2.0	9.0 $\pm$ 2.2	9.6 $\pm$ 1.4
VO_2 ($\text{L} \cdot \text{min}^{-1}$)	1.3 $\pm$ 0.42	1.4 $\pm$ 0.31	1.2 $\pm$ 0.25	0.7 $\pm$ 0.12	0.73 $\pm$ 0.08
RER	1.1 $\pm$ 0.03	1.1 $\pm$ 0.02	1.2 $\pm$ 0.08	1.1 $\pm$ 0.13	0.91 $\pm$ 0.04
HR	140 $\pm$ 27.2	148.5 $\pm$ 27.0	131.2 $\pm$ 28.2	116.7 $\pm$ 28.76	94.3 $\pm$ 21.5*
Vemax ($\text{L} \cdot \text{min}^{-1}$)	55.5 $\pm$ 13.8	56.0 $\pm$ 10.0	47.3 $\pm$ 11.0	—	—
AcKcal	38.3 $\pm$ 18.8	42.9 $\pm$ 14.9	36.1 $\pm$ 12.1	6.2 $\pm$ 4.5	10.54 $\pm$ 1.1
EE ($\text{kcal} \cdot \text{min}^{-1}$)	8 $\pm$ 2.1	7.9 $\pm$ 1.6	7.5 $\pm$ 1.5	3.4 $\pm$ 0.6	3.5 $\pm$ 0.3
RPE	18.9 $\pm$ 0.94	19.4 $\pm$ 0.72	19.2 $\pm$ 0.69	9.8 $\pm$ 2.4	11.5 $\pm$ 1.8
Workload (W)	62 $\pm$ 20.93	62 $\pm$ 17.37	61.3 $\pm$ 13.48	30	30
WE (%)	—	—	—	30.0 $\pm$ 7.4	31.9 $\pm$ 4.6
ME (%)	—	—	—	23.5 $\pm$ 7.5	20 $\pm$ 2.9

RS₁, RS trial 1; RS₂, RS trial 2; VO_2 ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), oxygen uptake; RER, respiratory exchange ratio; HR, heart rate; Vemax, pulmonary ventilation at $\text{VO}_{2\text{peak}}$; AcKcal, accumulated Kcal; EE ($\text{kcal} \cdot \text{min}^{-1}$), energy expenditure during exercise; RPE, ratings of perceived exertion; Workload (W), power output in watts; WE (%), work economy ($\text{VO}_{2-30\text{W}}$); ME (%), mechanical efficiency ($\text{VO}_{2-30\text{W}}$).

Figure 3 VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$) performance data for each participant in RS (trial 1) and ACE modalities. Open circles correspond to individual values; closed diamonds correspond to mean values. $N = 9$.

Figure 4 VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$) performance data for each participant in both RS trials. Open circles correspond to individual values; closed diamonds correspond to mean values. $N = 10$.

VO_2 ($P < 0.05$, $r = 0.79$), HR ($P < 0.01$, $r = 0.80$), AcKal ($P < 0.01$, $r = 0.81$), rate of energy expenditure ($P < 0.01$, $r = 0.90$), and RPE ($P < 0.01$, $r = 0.85$; Table 3). Peak pulmonary ventilation had a strong correlation ($P < 0.01$, $r = 0.87$) between testing modes, however approached significance ($P = 0.088$). Intra-class correlation coefficients revealed good reliability between RS trials, with significant moderate-to-strong correlations for VO_2 ($P < 0.01$, $r = 0.82$), AcKal ($P < 0.01$, $r = 0.91$), rate of energy expenditure ($P < 0.01$, $r = 0.94$), and peak power output ($P < 0.01$, $r = 0.98$; Table 3).

At submaximal exercise (30 W), HR was significantly higher for the RS compared to ACE; ($P < 0.05$); however, RPE, while only approaching significance, was higher for the ACE compared to the RS (Table 2), indicative of greater perceived exertion by participants with ACE despite equivalent workloads. No statistically significant difference existed between the RS and ACE mean values for ME; however, two participants exhibited considerably higher efficiency during RS testing compared to ACE (14.1% and 20.1% higher).

Bland-Altman plots were constructed for primary outcome measures to illustrate the limits of agreement and determine any potential bias between ACE and RS₁ (Figure 5) and RS trials (Figure 6). Between ACE and RS₁, mean differences for VO_2 , RER, and RPE were minimal (ranging from -0.29 – 0.33) with small limits of agreement. Between RS trials, mean differences for VO_2 , RER, and RPE were minimal as well (ranging from -0.82 – 0.021) with small limits of agreement. Mean differences for HR revealed greater bias for both ACE and RS₁ (-5.78 ; Figure 5c) and RS trials (-8.5 ; Figure 6c) comparisons. Notable outliers were

Table 3 Inter- and intra-class correlation coefficients of peak metabolic and submaximal (VO_{2-30W}) energetic values (r -values) during RS and ACE trials.

Variables	Interclass CC RS ₁ vs. ACE ($n = 9$)	Intraclass CC RS ₁ vs. RS ₂ ($n = 10$)
VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)	0.792 [†]	0.765*
RER	0.252	0.303
HR	0.801*	0.537 [†]
Vemax ($L \cdot min^{-1}$)	0.869*	0.783*
AcKcal	0.811*	0.886*
EE ($kcal \cdot min^{-1}$)	0.899*	0.906*
RPE	0.845*	0.120
Workload	0.775	0.968*
WE ^a	0.584	0.863*
ME ^a	0.133	0.677 [†]

^a $N = 10$.

[†]Correlation is significant at $P < 0.05$.

*Correlation is significant at $P < 0.01$.

Figure 5 Bland-Altman plots of primary outcome measures between ACE and RS₁; (a) VO₂, (b) respiratory exchange ratio, (c) heart rate, and (d) rate of perceived exertion. *N* = 9.

Figure 6 Bland-Altman plots of primary outcome measures between RS₁ and RS₂; (a) VO₂, (b) respiratory exchange ratio, (c) heart rate, and (d) rate of perceived exertion. *N* = 10.

present in the Bland-Altman plots of HR (Figures 5c and 6c) and RPE (Figures 5d and 6d).

Discussion

Our data suggest that measurement of peak cardiorespiratory capacity using the RS protocol is valid and reliable in MWUs with SCI. This was evidenced by participants exhibiting moderate-to-strong correlations of cardiorespiratory responses between the RS and ACE with no significant differences between the two testing modes. Additionally, no significant difference was found between the RS trials, indicating reliability and reproducibility of the testing protocol. At submaximal workloads, mechanical efficiency was slightly higher for the RS compared to the ACE; however, these results were not statistically significant. The only statistically significant result that existed was for HR; however, RPE approached significance between testing modes at submaximal workloads.

Bland-Altman plots of VO_2 , RER, and RPE further support the validity and reliability of the RS protocol. An outlier in the Bland-Altman plot of the ACE-RS₁, the HR measure is well outside the confidence interval and is also present in the plot of the same measure for RS₁-RS₂. Due to suppressed sympathetic activity of the central nervous system, HR is variable within and among individuals with tetraplegia,⁷ who comprised 70% of our sample. Both ACE-RS₁ and RS₁-RS₂ plots show an outlier for RPE. Upon review, a potential explanation for this outlier may be the participant's difficulty comprehending perceived exertion during the first RS trial, resulting in a short test time of 6 minutes and peak RPE of 16. The participant demonstrated improved understanding of the RPE scale during subsequent testing sessions (ACE and second RS trial), achieving an RPE of 20 for both tests.

Limited studies have examined the use of RS to assess cardiorespiratory fitness; to our knowledge, no other studies comparing $\text{VO}_{2\text{peak}}$ for persons with SCI during wheelchair dynamometry versus ACE, have been published. Mean $\text{VO}_{2\text{peak}}$ measured in the present study was similar to that found in previous studies of wheelchair ergometry and ACEs.^{15,19,35-37} Two previous studies^{16,33} reported higher $\text{VO}_{2\text{peak}}$ values than the present study, possibly reflecting the difference in sample populations; Torhaug and colleagues tested persons with paraplegia, and Wouda and colleagues focused on adults with SCI with an ASIA D classification. As 70% of participants from the present study had tetraplegia, we would expect mean $\text{VO}_{2\text{peak}}$ values to be lower, as less active muscle mass yields lower metabolic rates.^{38,39} According to

norm reference values for $\text{VO}_{2\text{peak}}$ for persons with SCI,^{15,19} our study cohort indicates excellent VO_2 performance for participants with tetraplegia and fair-to-average VO_2 performance for those with paraplegia. As 85% of our participants with tetraplegia participated in wheelchair sports and none of our participants with paraplegia played sports, we would expect to align with these fitness parameters.^{15,19}

Although mean $\text{VO}_{2\text{peak}}$ results were highly correlated across devices, these methods are not analogous in all aspects. ME did not significantly differ between testing modes; however, the RS tended to be slightly more efficient, potentially reflecting differences in task specificity between the two testing modes.^{16,40} The ACE requires participants to perform an unfamiliar, asynchronous movement,¹⁴ whereas the RS allows for use of a habituated propulsion pattern. The aerobic capacity of the working muscles plays a significant role in ME, whereas the more trained a particular muscle group is when performing a movement at a given workload, the greater the efficiency.⁴¹ Because wheelchair propulsion is the primary mode of mobility for MWUs with SCI, we would expect participants to be more efficient on the RS.

Despite similarities in VO_2 , participants consistently tended to rate subjective fatigue higher during ACE testing, indicating that participants perceived that they were working harder during the ACE test compared to the RS test. At 30 W, the ACE was fixed at 60 rpm, while the mean velocity maintained during RS testing was 41 rpm. These differences in speed may have resulted in higher RPE ratings for the same 30 W workload.^{16,33} The ACE also required participants to use an unfamiliar cranking motion and activate the trunk and/or upper extremity muscles to maintain an upright posture during testing. Wheelchair seating position is critical for lung function and activity performance for individuals with SCI, particularly those with tetraplegia.^{42,43} While approaching significance, peak pulmonary ventilation was higher during RS compared to ACE, possibly due to the postural differences during the testing modes.

Strengths

The protocol we used during the exercise tests on the RS seems to be suitable, and potentially superior, to the ACE protocol for this population. All participants achieved $\text{VO}_{2\text{peak}}$, according to the aforementioned criteria, during the RS tests; however, one participant failed to meet these criteria during his ACE test. The suboptimal postural positioning coupled with the standard crank velocity of 60 rpm required the participant

to challenge his strength over aerobic capacity, limiting his ability to achieve $\text{VO}_{2\text{peak}}$ before test termination. The present study supplements previous research findings that individuals with SCI are capable of performing high-intensity exercise.³³ However, the inherent heterogeneity of persons with SCI emphasizes the importance of individualizing exercise modes and programs to optimize health and fitness benefits. The RS used in the present study had the ability to control resistance based on each participant's maximal speed, promoting an individualized testing experience within a standard ramp protocol. RS, such as wheelchair ergometers, often use a standard laboratory wheelchair attached to the system potentially resulting in a suboptimal sitting position, ultimately impacting wheelchair propulsion performance.⁴⁴ The WMS allows participants to use their personal manual wheelchairs. While further empirical investigation is needed, exercise testing using an RS such as the WMS may provide a superior testing modality, as it promotes optimal positioning, the use of personal manual wheelchairs, a customizable ramp protocol with the manipulation of resistance, familiar movement patterns, and criteria standardization with individualized propulsion speeds.

Limitations

Due to the developmental and pilot nature of this study, a small sample size was used. Although levels of injury ranged from C₅ to T₁₁, only three participants had paraplegia, with most having injuries between C₅ and C₇. The sample size was also heavily skewed with 70% participating in wheelchair sports. Because 80% of adults with SCI are male,¹ female participants can be more difficult to recruit, thus leading our sample to include all males. Due to the inherent cardiovascular variability and impaired sympathetic stimulation of SCI, HR was not a primary determination criterion for $\text{VO}_{2\text{peak}}$, limiting the criteria used to RER and RPE.^{16,33,39} While HR is a common criterion omission, blood lactate threshold is often measured. The present study did not use lactate threshold as a criterion, which may have enhanced the results. The testing protocol may also not be appropriate or beneficial for individuals with injury levels above C₅, which account for approximately 20% of the SCI population,¹ due to significantly limited upper extremity function to propel a wheelchair or arm cranks. Another limitation of this study was the estimation of REE rather than a baseline measurement; because EE was calculated post hoc from a graded exercise test, the assumptions of steady state for calculating EE may have been violated, possibly impacting efficiency results. Finally, the ergometer used in the present

study used power as an input rather than a functional output of participants' work. This limitation of the ergometer may have constrained results comparing WE, ME, and peak power output.

Future research

Further development and research related to fitness testing and exercise programming may increase the application and validity of the specific RS used in this study as a testing protocol and exercise device. Future directions include the following areas: (1) including thoracic-level SCI, non-SCI MWUs, and non-athletic participants; (2) use of sports wheelchairs for exercise testing; and (3) exploration of the benefits and practicality of using an RS over the standard of care ACE within a clinical or research setting.

Conclusions

This study found $\text{VO}_{2\text{peak}}$ to be highly correlated between the two testing modes, indicating the RS protocol to be reliable and valid compared to the gold-standard ACE protocol. Differences in perceived exertion and efficiency at submaximal workloads and maximal pulmonary ventilation at peak workloads indicate potential advantages of the present RS protocol. To our knowledge, this is the only work comparing cardiorespiratory and energetic responses to maximal exercise testing between a roller-based wheelchair dynamometer and an ACE. The findings of this study have clinical implications by validating a newly developed exercise testing protocol that promotes task specificity and testing individualization. The specific RS used also has research applications for developing and assessing the effectiveness of exercise training programs for MWUs such as persons with SCI.

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Disclaimer statements

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JK, and WC contributed to data management, analysis, and interpretation. Substantial intellectual content was provided by KT related to all sections of the manuscript, ST related to the methods section, and all other authors related to the methods, results, and discussion sections. KM and KT drafted the manuscript. All authors critically revised the manuscript and gave final approval of the version to be published.

Conflicts of interest The authors declare no conflicts of interest.

Ethics approval The study was approved by the Washington University Human Research Protection Office. Prior to exercise tests, all participants obtained approval and signed release from a physician.

ORCID

Joseph W. Klaesner <http://orcid.org/0000-0002-6458-1719>

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