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Clinical Study

Arm Crank and Wheelchair Ergometry Produce Similar Peak Oxygen Uptake but Different Work Economy Values in Individuals with Spinal Cord Injury

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Objective. To study whether values for peak oxygen uptake (VO_{2peak}) and work economy (WE) at a standardized workload are different when tested by arm crank ergometry (ACE) and wheelchair ergometry (WCE). *Methods.* Twelve paraplegic men with spinal cord injury (SCI) in stable neurological condition participated in this cross-sectional repeated-measures study. We determined VO_{2peak} and peak power output (PO_{peak}) values during ACE and WCE in a work-matched protocol. Work economy was tested at a standardized workload of 30 Watts (W) for both ACE and WCE. *Results.* There were no significant differences in VO_{2peak} ($mL\cdot kg^{-1}\cdot min^{-1}$) between ACE ($27.3 \pm 3.2$) and WCE ($27.4 \pm 3.8$) trials, and a Bland-Altman plot shows that findings are within 95% level of agreement. WE or oxygen consumption at 30 W ($VO_{2\text{-}30W}$) was significantly lower during WCE compared to ACE ($P < 0.039$). Mean (95% CI) PO_{peak} (W) were 130 (111–138) and 100 (83–110) during ACE and WCE, respectively. *Conclusion.* The findings in the present study support the use of both ACE and WCE for testing peak oxygen uptake. However, WE differed between the two test modalities, meaning that less total energy is used to perform external work of 30 W during wheelchair exercise when using this WCE (VP100 Handisport ergometer). Clinical Trials Protocol Record is NCT00987155/4.2007.2271.

1. Introduction

Individuals with spinal cord injury (SCI) live an involuntary sedentary lifestyle that may result in reduced muscle mass and fat accumulation [1–3], impeding performance of exercises to improve cardiovascular health. Indeed, one of many negative health effects of SCI is an increased prevalence of cardiovascular disease (CVD), which is the leading cause of early death in this patient group [4, 5]. To prevent the possible development of CVD, it is mandatory that SCI individuals exercise with adequate training intensity in the same manner as able-bodied individuals to enhance and maintain cardiovascular fitness [6]. It is therefore important that training intensity is adjusted to individual exercise capacity as defined by peak oxygen uptake (VO_{2peak}) and power output (PO).

VO_{2peak} is a valid and sensitive outcome measure for assessing physical capacity in both able-bodied [7] and SCI individuals [5]. It should be a reliable determinant of cardiovascular fitness and a major predictor in the evaluation and treatment of the heightened CVD morbidity and overall mortality [5] for able-bodied [7] and SCI individuals. VO_{2peak} and power output (PO) in SCI individuals are most often tested using either arm crank ergometry (ACE) or wheelchair ergometry (WCE). It has been suggested that ACE is less strenuous than WCE [8–11]; however, the determination criteria for $\text{VO}_{2\text{peak}}$ measurements using ACE or WCE are inconsistent, resulting in disparate values. Sawka et al. [9] reported lower $\text{VO}_{2\text{peak}}$ and heart rate (HR) using ACE, while Hintzy et al. [12] found higher $\text{VO}_{2\text{peak}}$ and PO_{peak} values using ACE. Alternatively, Arabi et al. [13], Martel et al. [8], and Glaser et al. [14] all found no difference in $\text{VO}_{2\text{peak}}$ between ACE and WCE, while Hettinga and Andrews [15] reported that WCE resulted in higher $\text{VO}_{2\text{peak}}$ values. In addition to different determination criteria, these disparate $\text{VO}_{2\text{peak}}$ and PO values reported using ACE and WCE may reflect population heterogeneity and methodological diversity among studies.

Guidelines for improving cardiovascular aerobic fitness in SCI have been published [2, 16, 17]. Although recommendations on how to perform $\text{VO}_{2\text{peak}}$ tests in SCI individuals exist [8, 18], standardized determination criteria for a true $\text{VO}_{2\text{peak}}$ are still lacking. As previous studies have examined SCI individuals under different testing conditions (equipment and training intensities), it is of clinical value to test whether $\text{VO}_{2\text{peak}}$ and peak power output (PO) values derived from ACE and WCE are interchangeable. Therefore, ACE and WCE require more experimental research to reveal task-specific differences in cardiovascular capacity as to provide exercise recommendations. Although power output (PO) dependent gross mechanical work efficiency (ME; ratio of PO to energy expenditure) is a valid measure of overall improvement [19], peak power output and mechanical efficiency issues are complex and prone to overestimation [20]. Indeed, physical capacity varies considerably among SCI individuals, suggesting that standardized $\text{VO}_{2\text{peak}}$ and power output measurements are further developed to obtain comparative values for clinical practice and research [12, 21]. The collection of biomechanical and physiological data during wheelchair propulsion and arm ergometry should be performed on validated and calibrated medical equipment.

The main aim of this study was to investigate whether task-specific differences exist between ACE and WCE when $\text{VO}_{2\text{peak}}$ is measured using standardized and comparable test determination criteria. In addition, measurements were performed at 30 Watt ($\text{VO}_{2\text{-30W}}$) to examine whether there are differences in oxygen consumption required to perform external work (WE) between ACE and WCE.

2. Materials and Methods

2.1. Participants. Twelve male SCI individuals with sensory-motor complete injury (American Spinal Cord Injury Association Impairment Scale A (AIS A) to sensory-motor incomplete AIS C) were enrolled, all in a stable neurological state (Table 1). None of the participants were wheelchair athletes or were using performance enhancing or reducing (e.g., beta-blockers) drugs. None of the SCI individuals used abdominal binders or antithrombolytic stockings during testing. Candidate participants with a pacemaker, cancer, decubital ulcers, a medical history of unexpected autonomic dysreflexia, gross joint contractures, or acute shoulder girdle or joint tendonitis were excluded.

Table 1: Characteristics of SCI individuals included in the present study.

Subject	LOI/AIS	Age (y)	Ht (m)	Mass (kg)	TSI (y)
1	Th8/A	48	1.68	78	33
2	Th12/B	60	1.86	79	10
3	Th5/A	45	1.88	81	29
4	Th3/A	49	1.86	95	23
5	Th11/A	43	1.85	126	12
6	L1/A	35	1.78	78	11
7	L1/C	45	1.86	67	11
8	Th9/A	39	1.96	97	13
9	Th4/C	31	1.70	66	4
10	Th8/A	55	1.80	72	24
11	Th9/A	52	1.96	77	36
12	Th11/A	62	1.80	70	21
	Median	46.5	1.86	78.0	22
	Range	(31)	(28)	(60)	(26)

LOI: level of injury; AIS: American Spinal Injury Association Impairment Scale grade; Ht: height; TSI: time since injury.

Figure 1: The ACE experimental setup.

The study was approved by the Regional Committee for Medical Research Ethics and all participants provided informed consent prior to participation. We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed and that all procedures conformed to the latest revision of the Declaration of Helsinki.

2.2. Test Equipment and Measurements. An electromagnetically braked Ergomed 840 L (Siemens, Germany) was modified for asynchronous ACE. For WCE, the VP100 Handisport (Medical Development, France) was used as it has been shown to yield reproducible VO_2 measurements [22]. For WCE, the VP100 Handisport (Medical Development, France) (Figure 2) was used as it has been shown to yield reproducible VO_2 measurements [22]. For both ACE and WCE testing, all participants used their own rigid-frame wheelchair (Figures 1 and 2).

Prior to all tests, the ACE was calibrated according to the manufacturer's instructions (Siemens Ergomed Operation Manual, 1985) by bringing the ergometer to 90 revolutions per minute (rpm) before applying a braking force and measuring the time required for the rpm to decline to a given lower target. Specifically, the breaking time was correct to 35 rpm in 40 s with a 0 W braking load and to 0 rpm in 18 s using a 25 W

Figure 2: The WCE experimental setup.

braking load. To achieve horizontally aligned shoulder joint axes during ACE, wheelchairs were positioned on a steady platform and the elbows positioned slightly flexed at the point of furthest reach. The WCE equipment was calibrated by recording the total frictional rolling resistance (residual torque/moment of inertia) of zero load with participants in the normal sitting position and the wheelchair attached to the WCE [22].

All ventilation parameters and pulmonary gas exchange measurements were performed using the Metamax II Cortex ergospirometry system (Cortex Biophysik GmbH, Germany). A head cap assembly with facemask, volume transducer, and assembly tube for O_2 and CO_2 sensors was fixed on the participants during all tests. The volume range and accuracy were 0.01–14.0 $L{\cdot}s^{-1}$ and 1.5%, respectively. The oxygen concentration range and accuracy were 0–25 vol.% and <0.1 vol.%, respectively. CO_2 levels were analysed by an infrared sensor with a range from 0 to 10 vol.% and accuracy of <0.1 vol.%. The volume transducer was calibrated with a 3-L standardized calibration syringe (Hans Rudolph Jäger GmbH, Germany). The gas concentration sensors were calibrated with ambient air and a chemically standardized calibration gas comprised of 16% O_2, 4% CO_2, and 80% N_2 (SensorMedics Corporation, USA).

Blood lactate concentration ($[La^-]_b$ (mM)) was measured within one minute after termination of VO_{2peak} tests with an accuracy of ±3% using the Lactate Pro Analyzer LT-1710 (Arkray Factory, Inc., KDK Corp., Japan). Heart rate (HR) was measured with Polar® watches (Polar Electro, Oy, Finland) during all tests with accuracy of ±1 heart beat (Polar Operation manual, Polar Electro, 1997). For the subjective evaluation of perceived fatigue during tests, a rating scale of perceived exertion (RPE) from 6 to 20 (Borg 1970) was recorded during the last minute of the test.

Work economy (WE) was defined as oxygen consumption ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) divided by external work output (W) during steady state submaximal work. A constant 30-W workload ($VO_{2\text{-}30W}$) was used during WE measurements for both ACE and WCE to ensure submaximal aerobic conditions.

Mechanical efficiency (ME) was defined as external work output (W) divided by oxygen cost ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$). VO_2 and work output were converted to kcal ($Kcal{\cdot}min^{-1}$) to allow work economy to be expressed as percentage change.

2.3. Test Protocol. To minimize carry-over and order effects, the participants were randomly assigned to ACE or WCE as the first testing condition and there was a minimum 24-hours between tests. The test protocol for both ACE and WCE included: (1) a 6-min warm-up period; (2) $VO_{2\text{-}30W}$ testing for 4 min; (3) an individualized ramp protocol where work load was increased in steps varying from 5 W to 15 W (depending on the individual) in 1-min intervals, to reach VO_{2peak} as suggested by Froelicher [23]; (4) blood lactate ($[La^-]_b$) was measured within 1 min after termination of the peak test. The following determination criteria were used for VO_{2peak} [23]; Combined with a respiratory exchange ratio (RER) of ≥1.1, $[La^-]_b \geq 7$, and RPE ≥ 15 (Borg 6–20), VO_{2peak} was considered achieved. In the upper-body mode a VO_2 plateau (a VO_2 plateau, despite an increase in power output, and pulmonary ventilation) is rarely reached, therefore VO_{2peak} is used to denote maximal effort. If these criteria were met, the average of the highest VO_2 values within three consecutive 10 s measurements was calculated as VO_{2peak}.

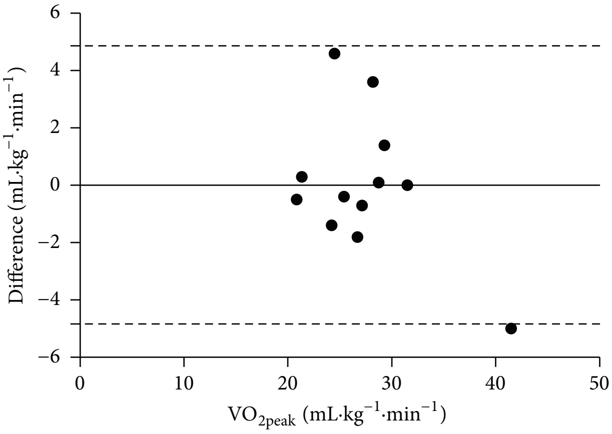

Figure 3: Bland-Altman plot shows differences in VO_{2peak} ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) between ACE and WCE within 95% of level of agreement.

2.4. Statistical Analysis. The nonparametric Wilcoxon signed-rank test was used to compare parameters between test conditions. Similarity was tested using Bland-Altman plot. Values are expressed as mean (standard deviation) or median (range). Significance was accepted at $P < 0.05$.

3. Results

The participants completed all tests without reporting severe fatigue, shoulder joint, or shoulder girdle pain. No observations on clinically relevant submaximal or peak heart rate disturbances were observed during the course of this study. The Bland-Altman plot shows 11 out of 12 points within the 95% level of agreement and thus a method similarity (Figure 3). There were no significant differences in VO_{2peak}, peak HR, peak VE, and peak RER values between ACE and WCE trials (Table 2 and Figure 4). At 30 W, VO_2 was 22% higher in ACE compared to WCE ($P < 0.039$; Table 2 and Figure 5), indicative of lower WE, and was associated with significantly higher HR and RPE. ACE generated a significantly higher ($P < 0.001$) peak power output (PO_{peak})

Table 2: Submaximal ($VO_{2\text{-}30W}$) and peak physiological values during arm crank ergometry (ACE) and wheelchair ergometry (WCE) presented as mean and confidence interval (CI) values.

Variables	ACE 30 W ($n = 12$)	WCE 30 W ($n = 12$)	ACE peak ($n = 12$)	WCE peak ($n = 12$)
VO_2 ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	10.9 (9.9–11.9)	9.0 (7.7–10.3)*	27.3 (24.1–30.5)	27.4 (23.6–31.2)
VO_2 ($L{\cdot}min^{-1}$)	0.87 (0.83–0.92)	0.72 (0.64–0.79)*	2.20 (1.98–2.42)	2.20 (1.96–2.44)
VE ($L{\cdot}min^{-1}$)	24.2 (22.8–25.7)	18.7 (17.7–22.8)*	95.7 (81.7–101.4)	93.9 (75.3–99.4)
RER	0.92 (0.88–0.94)	0.91 (0.87–0.93)	1.19 (1.16–1.25)	1.17 (1.11–1.23)
$[La^-]_b$ ($mmol{\cdot}L^{-1}$)			11.3 (9.1–13.4)	8.5 (7.6–9.3)*
HR	110 (56)	95 (85–109)*	179 (168–185)	173 (156–183)
RPE	10 (8–10)	7 (6–8)*	18 (17-18)	17 (16–18)
Workload (W)	30	30	130 (111–138)	100 (83–110)*

ACE 30 W: ACE at submaximal effort ($VO_{2\text{-}30W}$).
ACE peak: ACE at maximal effort (VO_{2peak}).
WCE 30 W: WCE at submaximal effort ($VO_{2\text{-}30W}$).
WCE peak: WCE at maximal effort (VO_{2peak}).
VO_2 ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$): Oxygen uptake.
VO_2 ($L{\cdot}min^{-1}$): Oxygen uptake.
VE ($L{\cdot}min^{-1}$): Pulmonary ventilation.
RER: Respiratory exchange ratio.
$[La^-]_b$ ($mmol{\cdot}L^{-1}$): Non-hemolyzed blood lactate concentration.
HR: beats.$\cdot min^{-1}$.
RPE: Rating of perceived exertion.
Workload: Power output in Watt.
Workload at peak: PO_{peak} in Watt.
*Level of significance $P < 0.05$.

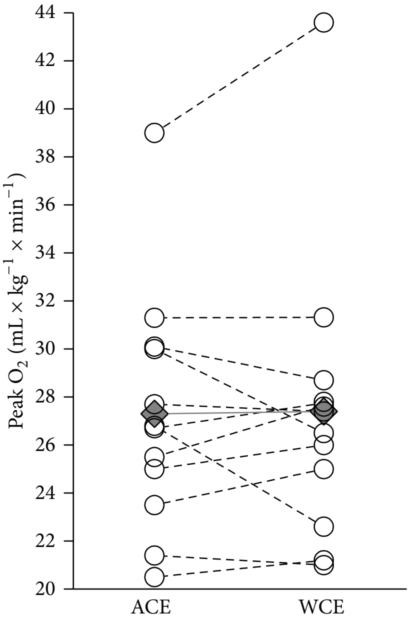

Figure 4: VO_{2peak} ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) performance data for all participants in the ACE and WCE modalities. Open circles correspond to individual values; diamonds correspond to median values. $N = 12$.

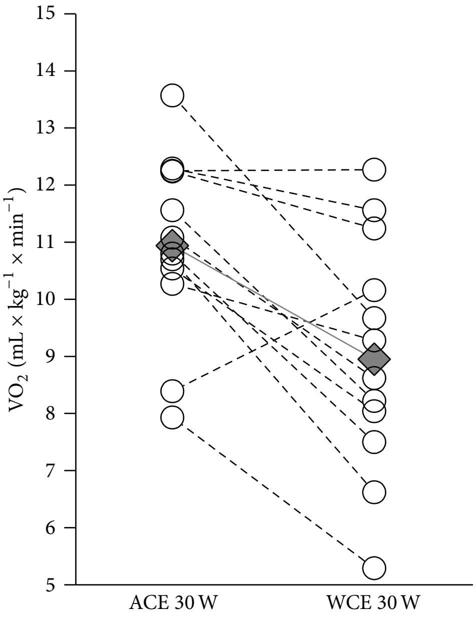

Figure 5: Steady state VO_2 ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) submaximal (30 W) data for all participants in the ACE and WCE modalities. Open circles correspond to individual values; diamonds correspond to median values. $N = 12$.

compared to WCE. In addition, $[La^-]_b$ was significantly higher during ACE. In the VO_{2peak} tests, two participants did not reach the determination criterion of $[La^-]_b \geq 7$ mM. However, excluding these two participants from the analysis did not influence the results. For the remaining 10 SCI individuals, median $[La^-]_b$ was still significantly higher following ACE compared to WCE (10.5 (7.9–14.9) mM versus 9.0 (7.4–10.6) mM; $P \leq 0.05$). Thus, in our statistical analysis, all 12 SCI individuals were included (Table 2).

4. Discussion

The main finding in the present study is that there is no significant difference between the two testing modes in terms of testing VO_{2peak}. This does not imply that the two methods are analogous, but rather that they may be equally appropriate for determining VO_{2peak} in individuals with SCI [14, 24]. Even if ACE and WCE show similar values for VO_{2peak}, the main muscles used to exert work seem different between the two modalities, that is, task specificity. Traditionally, VO_{2max} determination of able-bodied individuals is limited by cardiac output whereas for small muscle groups and not weight bearing activities as in ACE and WCE the limitations are primarily linked to the muscles' aerobic capacity. This makes the use of ACE or WCE and eventual differences between the working modes to a higher degree dependent upon the trained state of the muscles involved in the two different working modes. WE were lower using ACE, PO_{peak}, and HR higher, and ACE trials elicited greater subjective exertion ratings. Thus, ACE and WCE seem not to be comparable for submaximal levels of energy cost.

Mean VO_{2peak} values measured in this study were higher than in previous studies (ACE: 27 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ versus 19 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, [13]; WCE, 27 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$ versus 21 $mL{\cdot}kg^{-1}{\cdot}min^{-1}$, [25]), possibly due to population heterogeneity (i.e., the inherent VO_{2peak} levels of the study population). However, such differences may also reflect the lack of standardized determination criteria for VO_{2peak} in previous studies. Indeed, few studies have reported normative WCE-specific SCI VO_{2peak} values. According to Janssen et al. [26], WCE performance in our study cohort indicates average to good cardiovascular fitness. However, the aforementioned study [26] may have been somewhat biased since 40% of the SCI individuals were wheelchair athletes. On the basis of our findings, it appears that the SCI individual fitness levels from earlier studies may have been underestimated, underscoring the importance of defining a true VO_{2peak} via standardized determination criteria.

In the present study, the WE ($VO_{2\text{-}30W}$) was significantly higher during ACE compared to WCE (Table 2, Figure 5). The WE was approximately 20% lower on the WCE than using the ACE. A low oxygen cost is indicative of higher % work efficiency. This result contradicts earlier studies comparing VO_2 measurements by ACE and WCE, which reported ACE to be more efficient and effortless than WCE in terms of mechanical work efficiency (ME; work output divided by energy expended) [9, 27, 28]. The approximate ME for SCI individuals was reported to be 6% during WCE [11, 29] and 15% during ACE [30]. In the present study the ME is 14% and 21% for ACE and WCE, respectively. This may reflect differences in upper-body muscle activity elicited by ACE and WCE. Asynchronous ACE involves a 360° continuous push-and-pull application of force, while the pushing motion in WCE is discontinuous because of hand relocation between pushes. Thus, ACE might be considered a less complex and more continuous upper-body activity than WCE. Other differences may be pertinent as well. Most important is that the ergometers are completely different. The aforementioned studies have been using a different ergometer from the VP100 Handisport used in this comparison. It is difficult to compare the oxygen cost of work output across ergometers. In addition, the speeds of movement/cadence during the 30 W epochs differed between modalities; ACE was fixed at 70 rpm, while the mean optimal speed chosen by SCI individuals during WCE was 52 rpm. This may have resulted in velocity-dependent loss of efficiency during ACE. Indeed, the SCI individuals reported greater subjective fatigue and exhibited greater peak HR on ACE trials compared to WCE trials. The SCI individuals in the present study are also habituated to hand rim-propelled wheelchairs as an act of long-term daily mobility but are relatively inexperienced with asynchronous ACE, which may have further increased the difference in efficiency between ACE and WCE trials. Overall the differences in both ME and WE are considered to be limited to the particular ergometers used.

PO_{peak} values were significantly higher during ACE compared to WCE. Hintzy et al. [12] reported both higher VO_{2peak} and PO_{peak} values for ACE relative to WCE in able-bodied individuals, and Glaser et al. documented similar findings when comparing SCI to able-bodied individuals [14]. It has been suggested that physiological adaptations of the intact upper-body musculature in experienced paraplegic wheelchair ambulatory individuals contribute to this effect [14, 31]. Walker et al. [18] argued that an individualized high-intensity testing protocol (20 W/min increments per interval) elicits higher PO_{peak} and VO_{2peak} values. The mean PO_{peak} values during ACE and WCE reported in a recent SCI review, 85 W and 75 W, respectively [21], are lower than the values measured in the current study (130 W and 100 W), suggesting that our SCI individuals elicit a higher aerobic work performance. Another explanation may be that less of the total upper-body power production during WCE is transmitted to the ergometer, and therefore the ME seems reduced compared to ACE. Finally, Stewart et al. [24] obtained more reliable values for VO_2, HR, and RPE, with higher intraclass correlation coefficients in peak testing compared to submaximal testing. A lower reliability during submaximal tests and a reduced ME in WCE, therefore, may cause some of the measured differences in this study.

Alternatively, our findings are also comparable in several respects to studies [8, 14, 28] reporting lower ME and PO_{peak} values in WCE. Lower PO_{peak} values in WCE may be due to the fact that less of the total upper-body power production is transmitted to the ergometer, and therefore the MWE appears lower compared to ACE. A peak power loss of up to 30% has been calculated for WCE compared to ACE [8, 12, 14, 32]. Interestingly, adding 30% to our PO_{peak} WCE values brings the total PO to approximately 130 W, equalling that of ACE. In addition, the identical mean VO_{2peak} values for both ACE and WCE demonstrate that the total energy demands are identical despite the 30% lower PO_{peak} values during WCE [8, 24].

When blood lactate production ($[La^-]_b$) exceeds $[La^-]_b$ elimination, the anaerobic threshold is reached and muscle fatigue may occur [24, 31, 33]. In our study, peak values for HR and $[La^-]_b$ were significantly lower during WCE, indicating that $[La^-]_b$ accumulation in the blood occurred less rapidly than during ACE. This may be due to an inherent task-specific difference in upper-body capacity between WCE and ACE. These task-specific muscular characteristics were demonstrated by Schneider et al., who reported that the ACE $[La^-]_b$

threshold occurred at 58.9% of $\mathrm{VO}_{2\mathrm{peak}}$ in SCI individuals compared to 50% of $\mathrm{VO}_{2\mathrm{peak}}$ in able-bodied individuals [31]. The differences observed in our study indicate that the lactate $[\mathrm{La}^-]_\mathrm{b}$ threshold in WCE may occur at a higher percentage of $\mathrm{VO}_{2\mathrm{peak}}$ than in ACE. Thus, the specific upper-body muscles involved in ACE and WCE appear different even if the total recruitable upper-body muscle mass seems to be similar. Subsequently, there is most probably the total muscle mass in use that limits the $\mathrm{VO}_{2\mathrm{peak}}$. Therefore, the lower $[\mathrm{La}^-]_\mathrm{b}$ during WCE may reflect underlying differences in both the training specificities and muscular movement characteristics of the two modalities [34, 35], resulting in difficulty recruiting upper-body muscle mass during WCE compared to ACE [36].

The use of accurate $\mathrm{VO}_{2\mathrm{peak}}$ determination criteria is critical in defining true $\mathrm{VO}_{2\mathrm{peak}}$ values. Our main ACE and WCE $\mathrm{VO}_{2\mathrm{peak}}$ determination criteria are a respiratory exchange ratio (RER) of ≥ 1.1, $[\mathrm{La}^-]_\mathrm{b} \geq 7$, and $\mathrm{RPE} \geq 15$ (Borg 6–20). By including these criteria, the accuracy of measuring $\mathrm{VO}_{2\mathrm{peak}}$ may be enhanced. Moreover, these criteria may increase between-study comparability since $\mathrm{VO}_{2\mathrm{peak}}$ values obtained by ACE are comparable to those obtained by WCE.

In conclusion, for $\mathrm{VO}_{2\mathrm{peak}}$ testing, the two methods appear equivalent. The trained state of the muscle groups used for the one working mode over the other might however lead to differences. The SCI individuals in this experiment were used to both working modes, indicating that the amount of muscle mass involved seems to be relatively similar. However, if work economy is tested, ACE and WCE cannot be used interchangeably and seem to be highly dependent upon the ergometer used.

Abbreviations

$\mathrm{VO}_{2\mathrm{peak}}$:	Peak oxygen uptake
ACE:	Arm crank ergometry
WCE:	Wheel chair ergometry
WE:	Work economy
$\mathrm{PO}_{\mathrm{peak}}$:	Peak power output
PO:	Power output
VE:	Pulmonary ventilation
RER:	Respiratory exchange ratio
RPE:	Rating of perceived exertion
SCI:	Individuals with spinal cord injury
CVD:	Cardio vascular disease
HR:	Heart rate
$[\mathrm{La}^-]_\mathrm{b}$:	Blood lactate concentration
$\mathrm{VO}_{2\text{-}30\mathrm{W}}$:	Constant 30 W workload
ASIA:	American Spinal Cord Injury Association
AIS:	ASIA Impairment Scale
ME:	Mechanical efficiency.

Competing Interests

The authors declare that they have no competing interests and they certify that no party has a direct interest in the results of the research supporting this paper or will confer a benefit on them or on any organization with which they are associated.

Authors' Contributions

Tom Tørhaug and Berit Brurok carried out all the coordination, testing, drafting of the testing protocols and paper, design, and statistical analyses of the study. Jan Hoff, Jan Helgerud, and Gunnar Leivseth did drafting of the testing protocols, design, and statistical analyses of the study. All authors made a substantial intellectual contribution to the study to qualify for their authorship.

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References

[1] G. Bravo, G. Guízar-Sahagún, A. Ibarra, D. Centurión, and C. M. Villalón, "Cardiovascular alterations after spinal cord injury: an overview," *Current Medicinal Chemistry. Cardiovascular and Hematological Agents*, vol. 2, no. 2, pp. 133–148, 2004.

[2] P. L. Jacobs and M. S. Nash, "Exercise recommendations for individuals with spinal cord injury," *Sports Medicine*, vol. 34, no. 11, pp. 727–751, 2004.

[3] S. L. Groah, M. S. Nash, E. A. Ward et al., "Cardiometabolic risk in community-dwelling persons with chronic spinal cord injury," *Journal of Cardiopulmonary Rehabilitation and Prevention*, vol. 31, no. 2, pp. 73–80, 2011.

[4] M. J. DeVivo, K. J. Black, and S. L. Stover, "Causes of death during the first 12 years after spinal cord injury," *Archives of Physical Medicine and Rehabilitation*, vol. 74, no. 3, pp. 248–254, 1993.

[5] J. Myers, M. Lee, and J. Kiratli, "Cardiovascular disease in spinal cord injury: an overview of prevalence, risk, evaluation, and management," *American Journal of Physical Medicine and Rehabilitation*, vol. 86, no. 2, pp. 142–152, 2007.

[6] W. T. Phillips, "Effect of spinal cord injury on the heart and cardiovascular fitness," *Current Problems in Cardiology*, vol. 23, no. 11, pp. 649–716, 1998.

[7] J. Myers, M. Prakash, V. Froelicher, D. Do, S. Partington, and J. Edwin Atwood, "Exercise capacity and mortality among men referred for exercise testing," *The New England Journal of Medicine*, vol. 346, no. 11, pp. 793–801, 2002.

[8] G. Martel, L. Noreau, and J. Jobin, "Physiological responses to maximal exercise on arm cranking and wheelchair ergometer with paraplegics," *Paraplegia*, vol. 29, no. 7, pp. 447–456, 1991.

[9] M. N. Sawka, R. M. Glaser, S. W. Wilde, and T. C. Von Luhrte, "Metabolic and circulatory responses to wheelchair and arm crank exercise," *Journal of Applied Physiology Respiratory Environmental and Exercise Physiology*, vol. 49, no. 5, pp. 784–788, 1980.

[10] H. Tropp, "Power output for wheelchair driving on a treadmill compared with arm crank ergometry," *British Journal of Sports Medicine*, vol. 31, no. 1, pp. 41–44, 1997.

[11] L. H. V. van der Woude, H. E. J. Veeger, A. J. Dallmeijer, T. W. J. Janssen, and L. A. Rozendaal, "Biomechanics and physiology in

active manual wheelchair propulsion," *Medical Engineering and Physics*, vol. 23, no. 10, pp. 713–733, 2001.

[12] F. Hintzy, N. Tordi, and S. Perrey, "Muscular efficiency during arm cranking and wheelchair exercise: a comparison," *International Journal of Sports Medicine*, vol. 23, no. 6, pp. 408–414, 2002.

[13] H. Arabi, H. Vandewalle, P. Pitor, J. De Lattre, and H. Monod, "Relationship between maximal oxygen uptake on different ergometers, lean arm volume and strength in paraplegic subjects," *European Journal of Applied Physiology and Occupational Physiology*, vol. 76, no. 2, pp. 122–127, 1997.

[14] R. M. Glaser, M. N. Sawka, M. F. Brune, and S. W. Wilde, "Physiological responses to maximal effort wheelchair and arm crank ergometry," *Journal of Applied Physiology*, vol. 48, no. 6, pp. 1060–1064, 1980.

[15] D. M. Hettinga and B. J. Andrews, "Oxygen consumption during functional electrical stimulation-assisted exercise in persons with spinal cord injury: implications for fitness and health," *Sports Medicine*, vol. 38, no. 10, pp. 825–838, 2008.

[16] M. D. Hoffmann, "Cardiorespiratory fitness and training in quadriplegics and paraplegics," *Sports Medicine*, vol. 3, no. 5, pp. 312–330, 1986.

[17] K. A. Ginis, A. L. Hicks, A. E. Latimerm et al., "The development of evidence-informed physical activity guidelines for adults with spinal cord injury," *Spinal Cord*, vol. 49, no. 11, pp. 1088–1096, 2011.

[18] R. Walker, S. Powers, and M. K. Stuart, "Peak oxygen uptake in arm ergometry: effects of testing protocol," *British Journal of Sports Medicine*, vol. 20, no. 1, pp. 25–26, 1986.

[19] S. de Groot, A. J. Dallmeijer, O. J. Kilkens et al., "Course of gross mechanical efficiency in handrim wheelchair propulsion during rehabilitation of people with spinal cord injury: a prospective cohort study," *Archives of Physical Medicine and Rehabilitation*, vol. 86, no. 7, pp. 1452–1460, 2005.

[20] S. de Groot, M. Zuidgeest, and L. H. V. van der Woude, "Standardization of measuring power output during wheelchair propulsion on a treadmill," *Medical Engineering and Physics*, vol. 28, no. 6, pp. 604–612, 2006.

[21] J. A. Haisma, L. H. V. van der Woude, H. J. Stam, M. P. Bergen, T. A. R. Sluis, and J. B. J. Bussmann, "Physical capacity in wheelchair-dependent persons with a spinal cord injury: a critical review of the literature," *Spinal Cord*, vol. 44, no. 11, pp. 642–652, 2006.

[22] X. Devillard, P. Calmels, B. Sauvignet et al., "Validation of a new ergometer adapted to all types of manual wheelchair," *European Journal of Applied Physiology*, vol. 85, no. 5, pp. 479–485, 2001.

[23] V. Froelicher, *Exercise and the Heart*, WB Saunders, Elsevier, 5th edition, 2006.

[24] M. W. Stewart, S. L. Melton-Rogers, S. Morrison, and S. F. Figoni, "The measurement properties of fitness measures and health status for persons with spinal cord injuries," *Archives of Physical Medicine and Rehabilitation*, vol. 81, no. 4, pp. 394–400, 2000.

[25] L. Noreau, R. J. Shephard, C. Simard, G. Paré, and P. Pomerleau, "Relationship of impairment and functional ability to habitual activity and fitness following spinal cord injury," *International Journal of Rehabilitation Research*, vol. 16, no. 4, pp. 265–275, 1993.

[26] T. W. J. Janssen, A. J. Dallmeijer, D. Veeger, and L. H. V. Van Der Woude, "Normative values and determinants of physical capacity in individuals with spinal cord injury," *Journal of Rehabilitation Research and Development*, vol. 39, no. 1, pp. 29–39, 2002.

[27] A. J. Dallmeijer, L. H. V. Van der Woude, H. E. J. Veeger, and A. P. Hollander, "Effectiveness of force application in manual wheelchair propulsion in persons with spinal cord injuries," *American Journal of Physical Medicine and Rehabilitation*, vol. 77, no. 3, pp. 213–221, 1998.

[28] A. J. Dallmeijer, I. D. B. Zentgraaff, N. I. Zijp, and L. H. V. Van Der Woude, "Submaximal physical strain and peak performance in handcycling versus handrim wheelchair propulsion," *Spinal Cord*, vol. 42, no. 2, pp. 91–98, 2004.

[29] L. H. V. van der Woude, K. M. M. Hendrich, H. E. J. Veeger et al., "Manual wheelchair propulsion: effects of power output on physiology and technique," *Medicine and Science in Sports and Exercise*, vol. 20, no. 1, pp. 70–78, 1988.

[30] M. N. Sawka, "Physiology of upper body exercise," *Exercise and Sport Sciences Reviews*, vol. 14, no. 1, pp. 175–211, 1986.

[31] D. A. Schneider, D. A. Sedlock, E. Gass, and G. Gass, "$V^{\bullet}O_{2\mathrm{peak}}$ and the gas-exchange anaerobic threshold during incremental arm cranking in able-bodied and paraplegic men," *European Journal of Applied Physiology and Occupational Physiology*, vol. 80, no. 4, pp. 292–297, 1999.

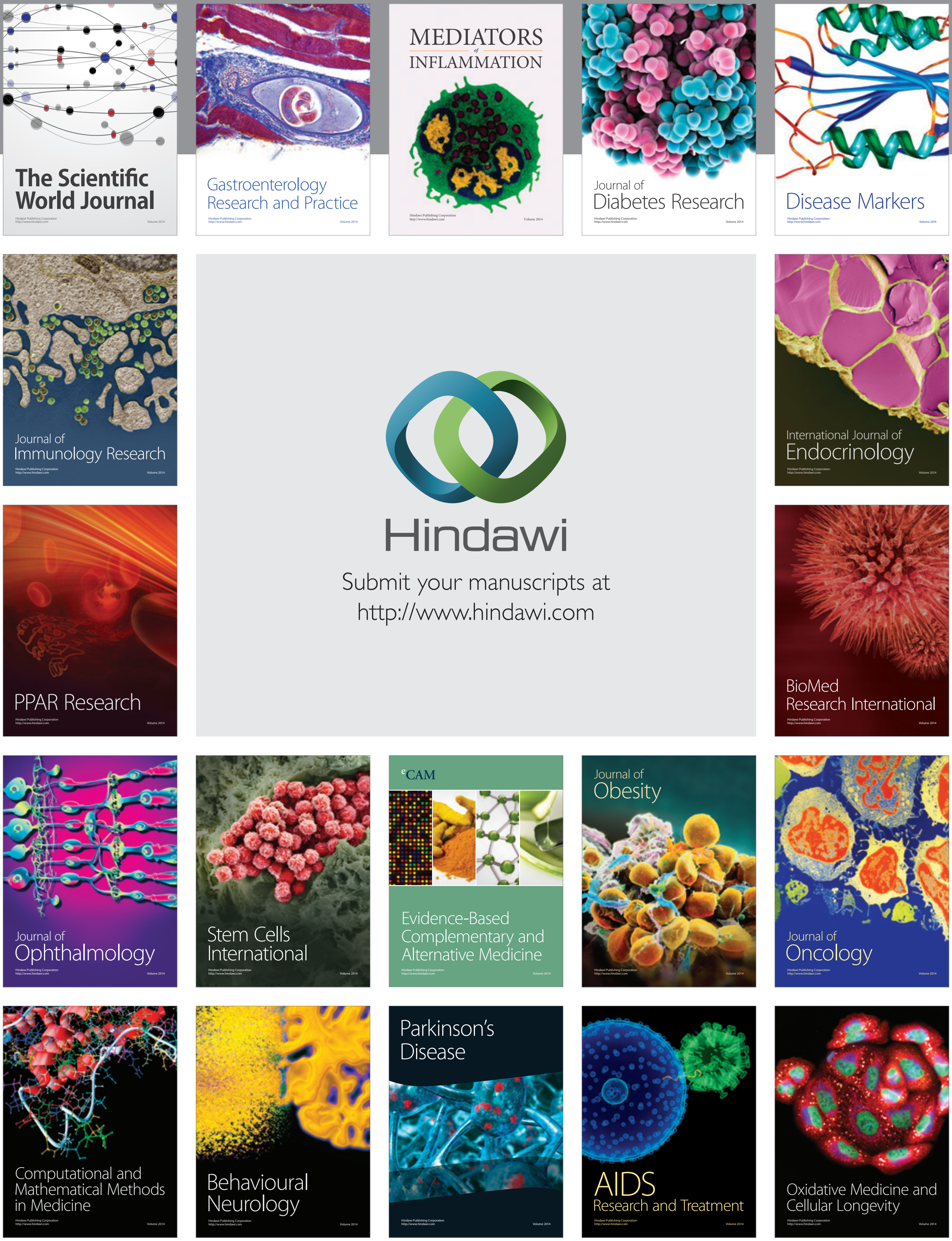
[32] L. H. V. van der Woude, A. J. Dallmeijer, T. W. J. Janssen, and D. Veeger, "Alternative modes of manual wheelchair ambulation: an overview," *American Journal of Physical Medicine & Rehabilitation*, vol. 80, no. 10, pp. 765–777, 2001.

[33] W. D. McArdle, F. I. Katch, and V. L. Katch, *Essentials of Exercise Physiology*, Lippincott Williams & Wilkins, Philadelphia, Pa, USA, 5th edition, 2011.

[34] Y. Fukuoka, R. Nakanishi, H. Ueoka, A. Kitano, K. Takeshita, and M. Itoh, "Effects of wheelchair training on VO_2 kinetics in the participants with spinal-cord injury," *Disability and Rehabilitation: Assistive Technology*, vol. 1, no. 3, pp. 167–174, 2006.

[35] Y. Fukuoka, M. Endo, H. Kagawa, M. Itoh, and R. Nakanishi, "Kinetics and steady-state of ${}_V\mathrm{O}_2$ responses to arm exercise in trained spinal cord injury humans," *Spinal Cord*, vol. 40, no. 12, pp. 631–638, 2002.

[36] E. M. Gass, L. A. Harvey, and G. C. Gass, "Maximal physiological responses during arm cranking and treadmill wheelchair propulsion in T4-T6 paraplegic men," *Paraplegia*, vol. 33, no. 5, pp. 267–270, 1995.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