Physiological Responses to Exergaming After Spinal Cord Injury

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Purpose: To investigate whether exergaming satisfies guideline-based intensity standards for exercise conditioning (40%/50% oxygen uptake reserve [VO_2R] or heart rate reserve (HRR), or 64%/70% of peak heart rate [HR_{peak}]) in persons with paraplegia. **Methods:** Nine men and women (18-65 years old) with chronic paraplegia (T1-L1, AIS A-C) underwent intensity-graded arm cycle exercise (AE) to evaluate VO_{2peak} and HR_{peak}. On 2 randomized nonconsecutive days, participants underwent graded exercise using a custom arm cycle ergometer that controls the video display of a Nintendo Gamecube (GameCycle; Three Rivers Holdings LLC, Mesa, AZ) or 15 minutes of incrementally wrist-weighted tennis gameplay against a televised opponent (XaviX Tennis System; SSD Co Ltd, Kusatsu, Japan). **Results:** GameCycle exergaming (GCE) resistance settings ≥0.88 Nm evoked on average ≥50% VO_2R. During XaviX Tennis System exergaming (XTSE) with wrist weights ≥2 lbs, average VO_2 reached a plateau of ~40% VO_2R. Measurements of HR were highly variable and reached average values ≥50% HRR during GCE at resistance settings ≥0.88 Nm. During XTSE, average HR did not reach threshold levels based on HRR for any wrist weight (20%-35% HRR). **Conclusions:** On average, intensity responses to GCE at resistance setting ≥0.88 Nm were sufficient to elicit exercise intensities needed to promote cardiorespiratory fitness in individuals with SCI. The ability of XTSE to elicit cardiorespiratory fitness benefits is most likely limited to individuals with very low fitness levels and may become subminimal with time if used as a conditioning stimulus. **Key words:** *exercise guidelines, exercise prescription, spinal cord injury, video game*

Significantly diminished levels of physical fitness are commonly reported in persons with spinal cord injuries (SCIs).[1] A sedentary lifestyle imposed on these individuals by paralysis has ranked them at the lowest end of the human fitness continuum.[2] In many cases, their suboptimal level of fitness challenges their ability to perform essential daily tasks.[3] It also increases their risks for commonly reported lipid disorders, insulin resistance, obesity,[4] and cardiovascular disease (CVD).[1,5,6] These health risks have led many health care professionals to strongly recommend that persons with SCI adopt regular physical activity as a lifestyle habit insofar as their disabilities allow.[7] These recommendations are supported by the section on Physical Activity for People with Disabilities contained in the 2008 Physical Activity Guidelines for Americans (Office of Disease Prevention & Health Promotion, US Department of Health and Human Services).

Evidence-based guidelines to achieve optimal fitness have been widely reported for persons without disability, and they typically specify an exercise prescription of recommended exercise frequency, duration, intensity, and mode of activity.[8,9] If adhered to, the prescription is designed to improve fitness without invoking injury or illness from excessive activity. Training studies conducted on persons with SCI having spared adrenergic function (ie, SCI below the T1 spinal level) have lead to the establishment of similar guidelines, which serve as benchmarks for exercise conditioning and health maintenance after SCI.[1,10]

The prescription of target exercise frequencies and durations for persons with SCI is not overly challenging, although poor exercise compliance presents a universal problem in exercise programming. Therefore, selection of an interesting and enjoyable exercise mode represents the bedrock of a successful exercise prescription. To this end, interest has recently focused on development and testing of enhanced exercise settings and exertional interfaces that form gameplay and virtual exercise environments. The ability of these exergaming systems to serve as surrogate exercise modes has been tested in older adults, children, and persons with motor impairment following stroke.[11-13] Various

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commercial exergaming products are available, (Dance Dance Revolution, Konami, Tokyo, Japan; Play Station 2 EyeToy: Kinetics, Sony, Tokyo, Japan; Wii Fit, Nintendo, Kyoto, Japan; and In the Groove, RedOctane, Mountain View, California), and devices have been implemented in a variety of settings (community centers, hospitals, and schools) as innovative and motivating tools to promote physical activity.[14] It stands to reason that exergaming may provide a similar choice in exercise programming for persons with disabilities. However, exergaming must invoke physiological responses that satisfy fitness thresholds already established to improve health and conditioning. According to the American College of Sports Medicine (ACSM), in most cases an exercise intensity of 40% and 50% (40%/50%) to 85% of oxygen uptake reserve (VO_2R) or heart rate reserve (HRR) is sufficient to achieve these overarching conditioning goals.[15] Alternatively, 64% and 70% (64%/70%) to 94% of maximal heart rate (HR_{max}) can also be used to identify intensity thresholds for cardiorespiratory (CR) fitness improvement[15]; however, for the sake of simplicity, the remainder of this article will focus on the thresholds related to reserve values. In significantly deconditioned persons, intensities as low as 30% of VO_2R are sufficient early in training, but need to increase thereafter.[15] Evidence regarding the ability of exergaming devices to satisfy these intensity targets in persons with SCI is limited. Investigations of a custom wheelchair roller system–computer interface reported increased HR and VO_2 for wheelchair ergometry with a video game.[16,17] A similar device using arm cycle ergometry (AE) showed comparable results.[18] Wheelchair ergometry exergaming was also reported to elicit intensities sufficient for an exercise training response, however the criteria used to make this determination did not represent current ACSM standards and instead were estimated based on a submaximal test not validated for arm work.[19] In adolescent patients with spina bifida, arm cycle ergometer exergaming successfully satisfied the aforementioned exercise intensity targets.[20] However, for individuals with SCI no evaluation of exergaming intensities in direct comparison to peak aerobic capacity and authoritative intensity thresholds for CR fitness promotion has been published to date.

Therefore, the purpose of this study was to examine whether persons with chronic paraplegia undergoing multistage graded exercise using a custom arm cycle ergometer that controls the video display of a Nintendo Gamecube (GameCycle, Three Rivers Holdings LLC, Mesa, Arizona) or 15 minutes of incrementally wrist-weighted tennis gameplay against a televised opponent (XaviX Tennis System, SSD Co Ltd, Kusatsu, Japan) experience a metabolic response sufficient in intensity to satisfy authoritative exercise guidelines. We hypothesized that GameCycle exergaming (GCE) and XaviX Tennis System exergaming (XTSE) would elicit exercise intensities that meet authoritative threshold criteria.

Methods

Subjects

Participants for this cross-sectional analysis were 9 men and women aged 18 to 65 years with paraplegia at the T1-L1 levels (AIS A-C) for longer than 1 year (**Table 1**). Study candidates were excluded from testing if they had pain in the shoulders or arms that limited exercise or if they had been instructed by a physician to not exercise. All testing procedures were explained, and subjects provided written informed consent in accordance with the guidelines established by the Institutional Medical Sciences Committee for the Protection of Human Subjects.

Protocol

Testing took place on 3 nonconsecutive days within a 2-week period. On the first day, study participants came to the testing laboratory where they became familiar with the GameCycle and a XaviX Tennis System. Thereafter, study participants underwent a multistage, intensity-graded arm exercise test to exhaustion. Responses to exercise were continuously monitored via open-circuit spirometry and 12-lead electrocardiography (Vmax Spectra 229c with integrated electrocardiographic monitoring; CareFusion

Table 1. Subject characteristics

Subject	Age, years	Height, m	Weight, kg	Level of injury	Years injured
A	28	1.83	77.7	T10	11
B	34	1.93	99.5	T4	8
C	25	1.91	106.4	T5/T6	8
D	62	1.75	84.1	T7	3
E	20	1.78	62.3	T4	4
F	64	1.83	86.8	T4-5	14
G	64	1.65	72.2	T7	11
H	23	1.7	72.7	T3	13
I	40	1.65	60.9	T6	8
Mean	34	1.74	69.3	N/A	9.5
SD	8	0.13	11.9	N/A	2.1

Note: N/A = not applicable.

Corp, San Diego, California). Subjects were prepared with a 12-lead electrode array to monitor exercise ECG and had a Hans Rudolph soft mask placed over their nose and mouth to collect expired air. They were allowed 5 minutes of quiet rest while baseline data were gathered. Subjects then propelled the ergometer in 3-minute stages starting without applied resistance and increasing 20 W thereafter. Exercise termination was consistent with the *Guidelines of the American College of Sports Medicine for Exercise Testing and Prescription* (7th ed),[1] with cessation caused by fatigue, inability to maintain propulsion rate, or a decrease in VO_2 or HR accompanying increasing workload. Postexercise ECG was monitored for 10 minutes as a safety precaution.

On 2 randomized nonconsecutive days within 1 week of exercise testing study, participants underwent a single bout of exergaming using the GameCycle and XaviX Tennis System. On both days, subjects were monitored with a portable spirometric system (OxyconMobile, CareFusion Respiratory Care, Yorba Linda, California) and integrated HR telemetry using a Polar chest strap (Polar Electro Inc, Lake Success, New York).

GameCycle testing

Before testing, subjects were fitted with the measurement equipment described previously. Metabolic data were collected during 5 minutes of rest and during all stages of exercise. GameCycle resistance was applied in increments of 0.88 Nm (level 1 through 9). The GameCube disc "Need for Speed" was started; subjects began to exercise at level 1 and increased the resistance level every 3 minutes until volitional exhaustion. Subjects were allowed to self-select their pace in order to maintain the flow of game play. Metabolic measurements were monitored for 10 minutes after the test had been completed. Subjects were provided cool water and a towel to dry off.

XaviX Tennis System testing

Before testing, subjects were fitted with measurement equipment described previously. Subjects engaged in 15 minutes of game play against an interactive opponent on a television screen using the XaviX Tennis System. Subjects exercised by swinging a shortened tennis racquet in response to a virtual ball being hit to them by an opponent on the television screen. Subjects began exercising without resistance and had a 1.0 lb cuff weight added to their wrist every 3 minutes (up to 4 lbs). Metabolic data were collected during 5 minutes of rest, 15 minutes of exercise, and 10 minutes after the test had been completed. Subjects were provided cool water and a towel to dry off.

Calculations for $\%VO_2R$ and %HRR were performed as follows:

$$\%VO_2R = 100 \cdot [VO_2 / (VO_{2peak} - VO_{2rest})]$$
$$\%HRR = 100 \cdot [HR / (HR_{peak} - HR_{rest})]$$

where VO_2 and HR were the 3-minute averages for each exercise stage, VO_{2peak} and HR_{peak} were the peak values attained on the arm ergometry test, and VO_{2rest} and HR_{rest} were the 5-minute resting averages measured before exercise.

Statistical analysis

Data are presented as mean ± *SD*. Differences between exercise modes were analyzed by analysis of variance (ANOVA) with repeated measures followed by post hoc analyses using the least significant difference test. Association between HR and VO_2 was assessed with simple regression analysis. Significance was set a priori at $\alpha < 0.05$.

Results

VO_2 and HR as measured during GCE and XTSE are shown in **Figure 1** and are displayed as relative to AE-derived VO_2R and HRR. Peak VO_2 and HR values reached during each mode of exercise are presented in **Figure 2**. Peak values reached during AE and GCE did not differ significantly from each other but were both significantly higher than those achieved during XTSE. During GCE, all subjects completed the exercise stage for resistance level 4 (3.52 Nm), although most (n = 6) subjects could not complete 3 minutes of work at a resistance level greater than 7 (6.15 Nm) (**Table 2**). The majority of subjects (n = 5) reached intensities ≥50% of AE-derived VO_2R at all resistance levels during GCE, and all reached this threshold at their individual peak resistance level (**Table 2**). All subjects were able to complete XTSE with all wrist weights (0-4 lbs). During XTSE, no more than 3 subjects reached exercise intensities ≥40% of AE-derived VO_2R for any given wrist weight irrespective of the load, but the majority of subjects (n = 5) did reach this threshold at their individual peak (**Table 3**).

Heart rates were not well associated with VO_2, for AE (adjusted $r^2 = .081$, $P = .087$), GCE (adjusted $r^2 = .269$, $P = .001$) and XTSE (adjusted $r^2 = .277$, $P < .001$), respectively. Data for regression were limited to AE stages 1 to 3 and GCE resistance level 1 to 4 (0.88-3.52 Nm), because not all subjects were able to continue exercise beyond these levels. The majority (n = 5) of subjects reached HR ≥40% of AE-derived HRR at resistance level ≥1 (0.88 Nm) for GCE and at least half reached values ≥50% of AE-derived HRR (**Table 2**). All reached the latter threshold at their individual peak during GCE. During XTSE, maximally, half of the subjects reached HR ≥40% of AE-derived HRR and no more than 3 reached values ≥50% of AE-derived HRR, independent of wrist weight used (**Table 3**).

Discussion

The main finding of this investigation was that GCE elicits exercise intensities that satisfy authoritative exercise guidelines for individuals with paraplegia. XTSE satisfied these criteria in only 5 out of 9 subjects.

The findings of this study suggest that interactive exergaming represents an effective mode to elicit intensities capable of improving CR fitness in persons with paraplegia with exercise training. Similar exercise intensities used for physical conditioning have improved atherogenic lipid profiles in the same population, suggesting a reduction of CVD risk. Marked physical deconditioning is common after SCI,[2,3,7] and the degree of physical fitness is an important factor regarding risk for CVD. Daily wheelchair use and activities of daily living are insufficient to either improve or maintain cardiopulmonary fitness.[21,22] Exercise interventions are therefore necessary to improve CR fitness after SCI. Fewer exercise options are available to persons with SCI compared to those without disability,[23] and this may be a limiting factor when an exercise regimen is begun.

Arm crank and wheelchair ergometry are known to be the most widely used exercise modes for clinical and functional evaluation of exercise performance. The former is the most available equipment for an upper limb exercise conditioning program.[24-27] However, use of these modes may elicit boredom resulting in lack of motivation and exercise noncompliance. Technologies that integrate video gameplay with exercise may be able to address these shortcomings; to be effective, these exergaming tools need to elicit exercise intensities sufficient to reach established

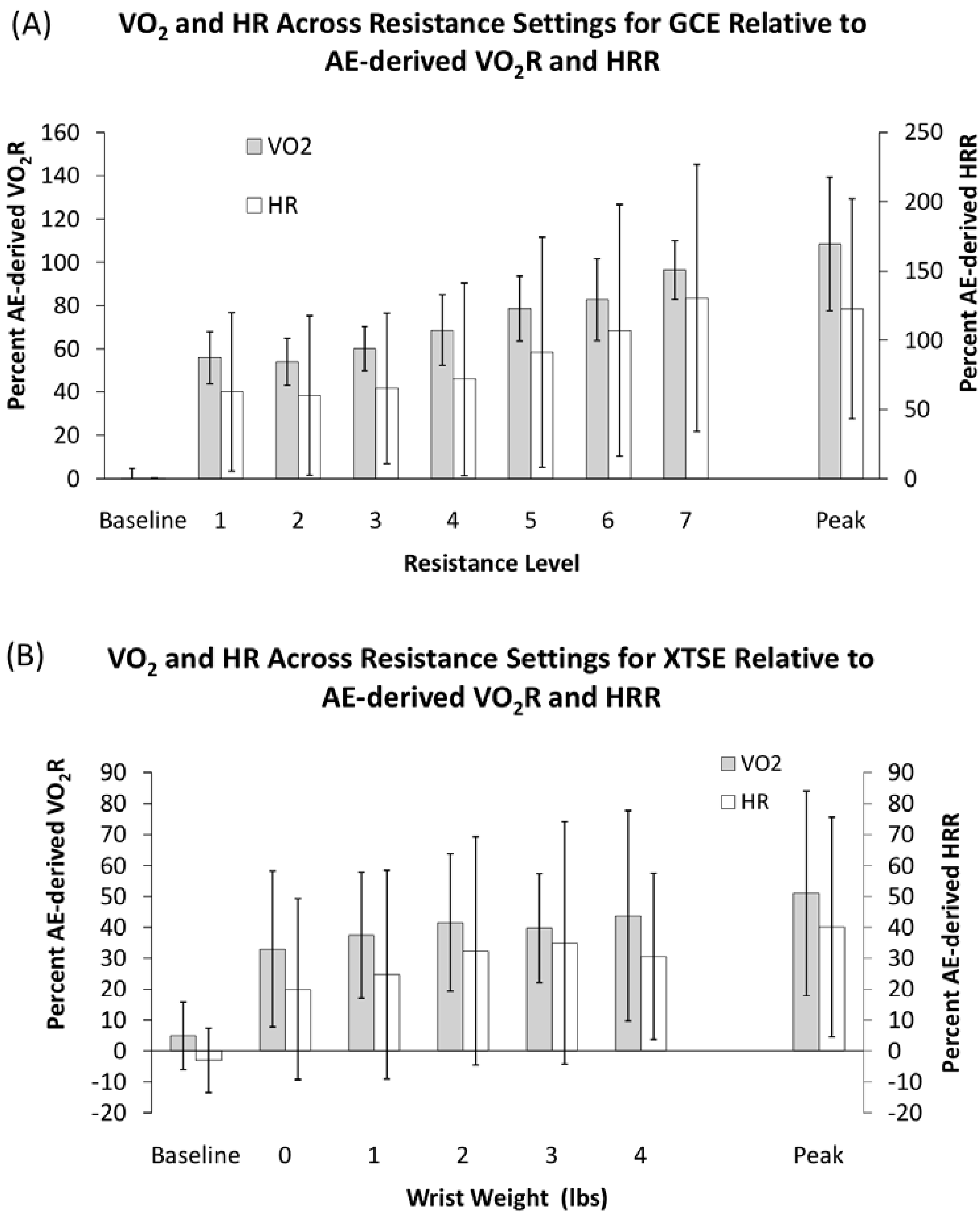

Figure 1. Oxygen consumption (VO_2) and heart rate (HR) across exergaming stages relative to the peak values for VO_2 and HR achieved during incremental arm cycle exercise (AE) to volitional exhaustion. (A) GameCycle exergaming (GCE). Values for baseline and resistance levels 1-7 (0.88-6.15 Nm) are for the subjects (n = 7) who completed at least resistance level 7 during GCE. Peak values represent the last completed stage during GCE for all (n = 9) subjects. (B) XaviX Tennis System exergaming (XTSE). Peak values are the highest values measured for XTSE with any of the wrist weights.

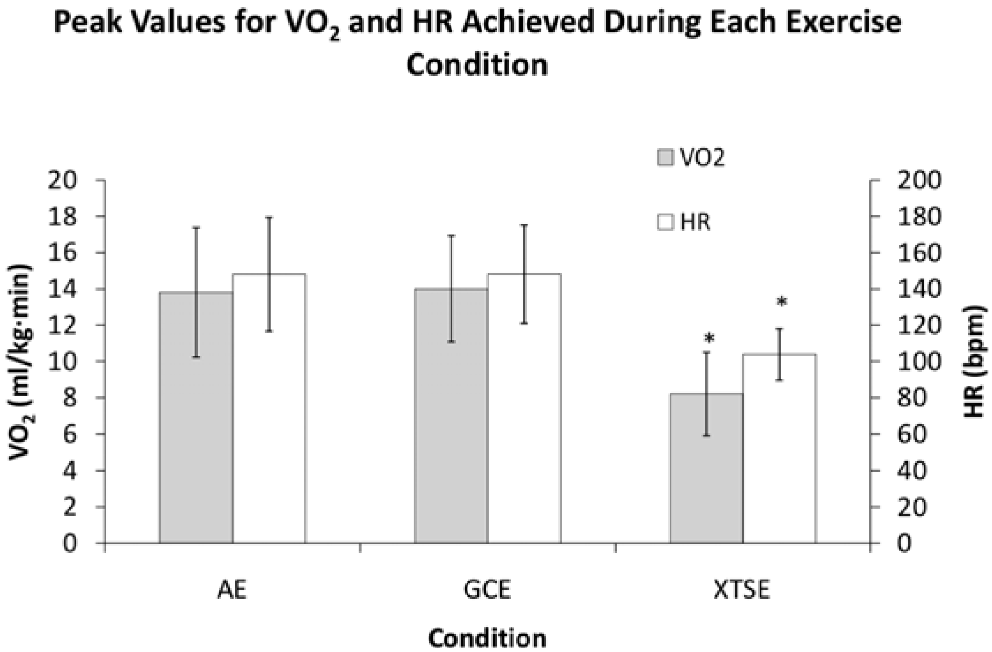

Figure 2. Peak values for oxygen consumption (VO_2) and heart rate (HR) achieved during each exercise condition. *Significantly different from arm cycle exercise (AE) and GameCycle exergaming (GCE) ($P < .05$).

thresholds for CR fitness improvement (40%/50% of VO_2R or HRR).[15] O'Connor and colleagues[16,17,19] reported that when integrating videogame play with wheelchair ergometry, individuals not only reached exercise training zone intensities (≥50% estimated VO_{2peak} and ≥60% estimated HR_{peak}), but they did so faster, maintained them throughout the trial, and elicited higher HR and VO_2 than the same exercise without a video game. Using a similar protocol with arm crank instead of wheel chair ergometry, Fitzgerald et al[18] reported increased VO_2 with exergaming compared to exercise on the same ergometer without gameplay (though no change in HR). To date, only one study investigated exergaming in relation to peak aerobic capacity in patients with spinal cord dysfunction. In that study, 6 out of 8 adolescent spina bifida patients undergoing exergaming with the GameCycle system reached ≥50% of VO_2R and 7 reached ≥50% of HRR.[20] The present investigation indicates even slightly better effectiveness for GCE in SCI individuals, with all reaching ≥50% of VO_2R. During XTSE, only 3 individuals reached this threshold. Nevertheless, for individuals with fitness levels intensities as low as 30% of VO_2R can elicit CR fitness improvements.[15] Only 2 subjects did not reach this threshold with XTSE, peaking at 25% and 28% of VO_2R, respectively.

All subjects in the present study reached ≥50% of HRR during GCE, even though the resistance levels that elicited this threshold varied considerably among subjects. Again, XTSE was less effective, with only 3 subjects reaching values ≥50% of HRR. It should be noted that estimating intensity by HRR, although convenient, may not be ideal for this population. Others have reported increased VO_2 with exergaming compared to match control exercise but no increase in HR.[18] This disconnect persisted even after subjects with tetraplegia were excluded from the analysis, leaving only 4 subjects with injuries at T6-8 and 5 with injuries T10 or lower.[18] Our results also indicated relatively poor associations between VO_2 and HR for all modes of exercise, but the study included 6 subjects with injuries at T3-6. It is known that patients with SCI at levels above T6 have abnormal cardiovascular

Table 2. Number of subjects reaching intensity thresholds during GameCycle exergaming

Resistance level (torque, Nm)	Number of subjects reaching intensity thresholds based on AE-derived VO2R (HRR)		No. of subjects who completed level
	40%-50%	≥50%	
1 (0.88)	3 (1)	5 (4)	9
2 (1.76)	3 (0)	5 (5)	9
3 (2.64)	3 (1)	6 (4)	9
4 (3.52)	2 (1)	7 (4)	9
5 (4.39)	0 (1)	8 (5)	8
6 (5.27)	0 (1)	8 (7)	8
7 (6.15)	0 (0)	7 (7)	7
8 (7.03)	0 (0)	3 (3)	3
9 (7.91)	0 (0)	2 (2)	2
Peak	0 (0)	9 (7)	9

Note: AE = arm cycle ergometry; VO_2R = oxygen uptake reserve; HRR = heart rate reserve; peak = peak value achieved during any resistance level for each subject.

Table 3. Number of subjects reaching intensity thresholds during XaviX Tennis System exergaming

Wrist weight, lbs	Number of subjects reaching intensity thresholds based on AE-derived VO_2R (HRR)		No. of subjects who completed level
	40%-50%	≥50%	
0	2 (1)	1 (3)	9
1	0 (0)	1 (3)	9
2	1 (0)	2 (2)	9
3	1 (1)	2 (3)	9
4	1 (1)	1 (2)	9
Peak	2 (2)	3 (2)	9

Note: AE = arm cycle ergometry; VO_2R = oxygen uptake reserve; HRR = heart rate reserve; peak = peak value achieved during any resistance level for each subject.

responses to exercise,[28] which could explain the poor association observed in the present study.

Limitations

The present study only included 9 participants. Low sample sizes are a common difficulty given the relative small population (~200,000 nationwide) and heterogeneity of SCI and its comorbidities. This imposes limitations on standard statistical techniques to identify significant differences and on the generalizability of findings.

Some individuals reached higher peak values during GCE than during the AE. This would indicate that they did not have their true peak as a reference value. However, guidelines are based on standard methods (such as AE) to derive peak values and therefore should be adequately reflected by the AE values. Furthermore, GCE and AE peak values were not statistically different from each other (**Figure 2**),

and only one subject exceeded AE-derived VO_{2peak} by more than ~10% during GCE.

Conclusions

For individuals with paraplegia, exergaming using a commercially available arm crank ergometer was efficient in eliciting exercise intensity thresholds that satisfy authoritative guidelines for CR fitness promotion. The effectiveness of exergaming using a commercial tennis game could be used for most persons with paraplegia who have very low fitness levels. Study participants reported enjoying the exergaming exercise, although future work will have to establish whether exergaming is able to stimulate motivation and exercise adherence in persons with SCI.

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