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Chronotropic Incompetence Does Not Impede Attainment of High-Intensity Exercise During Non-Contact Boxing in Parkinson's Disease

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Abstract: Recent evidence points to the effect of chronotropic incompetence (CI), which refers to a blunted heart rate (HR) response to exercise, influencing physiological outcomes in people with Parkinson's disease (PD). This study explores the effect of CI on physiological responses and examines whether a high-intensity training zone is attained during non-contact boxing training in people with PD. In total, 11 PD participants with CI (PDCI), 13 without CI (PD non-CI), and 14 age-matched controls performed two non-contact boxing sessions on different days. The primary outcomes were the maximum HR (HRmax), average HR (HRavg), percentage of the highest HR from cardiopulmonary exercise test (%HR-CPET) and predicted maximum HR (%MA-PHR), time exercising above 85%HRmax (HI-85%), and second ventilatory threshold (HI-VT2). PDCI participants displayed significantly lower HRavg and HRmax values during all rounds than PD non-CI participants and controls for both sessions ($p \leq 0.001$). No significant differences were observed between PD non-CI participants and controls ($p \geq 0.05$). Although all participants exercised at approximately 100% of %HR-CPET, PDCI participants showed a significantly lower %MA-PHR than PD non-CI participants and controls ($p \leq 0.001$). HI-85% and HI-VT2 were not significantly different between PDCI and PD non-CI participants. Despite exhibiting a lower absolute HRmax and HRavg during boxing compared to PD non-CI participants and aged-match controls, PDCI participants exercise at a similar intensity within the high-intensity training zone when expressed as a percentage of the individualized HRmax.

Keywords: Parkinson's disease; chronotropic incompetence; high-intensity interval training; non-contact boxing; cardiopulmonary exercise test

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1. Introduction

Non-contact boxing training, defined here as boxing, is popular amongst people with Parkinson's disease (PD) for management of the condition and improvement in general fitness [1–3]. It incorporates high-intensity interval training (HIIT), which has been shown to improve aerobic capacity in the general population and people with PD [4–10]. Boxing also requires intricate footwork and punches (exercise complexity) that challenge cognition and dynamic balance, which are particularly relevant to people with PD [11–14].

Combs and colleagues pioneered the feasibility and safety of boxing in PD through a case series and a randomized clinical trial, reporting enhanced balance, gait, and quality-of-life outcomes [15,16]. Subsequent studies showed that boxing interventions led to improvements in these outcomes, as well as cognitive function and depression [3,15–21]. The literature often refers to boxing as vigorous to high-intensity aerobic exercise for people with PD. However, studies do not always report the intensity zone achieved during boxing combinations or the effect of other non-boxing-related drills and activities often included in protocols that incorporate measures of exercise intensity [1,10,20,22–28]. Exercise intensity is an essential training variable for HIIT protocols and also a determinant of energy expenditure (EE) [6].

An important feature that may impact on exercise performance is the presence of an autonomic dysfunction, particularly chronotropic incompetence (CI). This feature is characterized by the incapacity to achieve a targeted threshold of 85% maximum age-predicted heart rate (MA-PHR) during peak exercise, even though clinical and physiological indicators suggest that maximal effort has been achieved [29,30]. CI affects between 10 and 50% of people with PD. Interest in its effect on exercise performance is growing, particularly during incremental maximal exercise testing and continuous aerobic protocols [31–35]. Studies to date have not examined physiological responses and the level of exercise intensity in people with PD with CI during boxing. While this activity is considered an alternative form of HIIT for the general population, this has yet to be examined systematically in people with PD.

This exploratory study had three key aims. The first was to examine the effect of CI on physiological and clinical responses during boxing sessions in people with PD. The second was to evaluate the percentage of time spent in the high-intensity training zone based on individualized physiological measures of exercise intensity. The last aim was to evaluate the energy expended during boxing sessions.

2. Materials and Methods

2.1. Participants

Participants with PD and healthy controls were recruited through Parkinson's New Zealand, community-based gyms, and organizations working with people with PD. Advertisements were placed in gyms, community notice boards, and via social media platforms. Inclusion criteria: the study included participants clinically diagnosed with PD without other neurodegenerative diseases and a score of 23 and above on the Montreal Cognitive Assessment (MoCA) [36]. Exclusion criteria for PD included marked gait impairment or postural instability based on the Movement Disorder Society Unified Parkinson's Disease Rating Scale (MDS-UPDRS) part III scores [37], a deep brain stimulation implant. Exclusion criteria for all participants included the use of a pacemaker or beta-blockers, the presence of heart conditions, or any other conditions contraindicated for HIIT [6].

Participants attended on three non-consecutive days. On the first day, participants underwent a cardiopulmonary exercise test (CPET) and on the second and third days they performed boxing sessions. Participants were instructed to avoid exercise for 24 h, abstain from alcohol and caffeine for 12 h, and refrain from consuming a large meal within 3 h of testing. PD participants were tested approximately one hour after medication to optimize their 'on' state. All testing took place at the Auckland University of Technology in the exercise performance laboratory under temperature-controlled conditions (19−20 °C).

2.2. Data Collection

Metabolic and heart rate (HR) data were collected breath by breath using a gas analyzer (MetaLyzer 3B; Cortex Biophysik, Leipzig, Germany) connected to MetaSoft Studio© software (version 5.13.0 SR2) during CPET and boxing sessions. The equipment was calibrated following the manufacturer's instructions prior to each test. A 12-lead electrocardiogram (Customed Cardio 300, Leipzig, Germany) recorded HR responses during

CPET, and Polar H10 (Polar Electro Oy, Kempele, Finland) sensor chest belt was used during boxing sessions. CPET breath by breath data were filtered using a 20 s moving time interval average utilizing MetaSoft Studio© software for determination of maximal and submaximal (first (VT1) and second (VT2) ventilatory thresholds) physiological measures according to high-reliability guidelines [35,38,39]. Breath by breath data collected during boxing sessions were exported to a text file. These were then interpolated and filtered using a moving average of five points using NI LabView software 2021 (National Instruments) to determine HR and metabolic responses.

2.3. Cardiopulmonary Exercise Test (CPET)

The CPET ramp protocol began with a warmup that involved three minutes cycling at 60 revolutions per minute (rpm) at a workload of 20 watts on an electronic cycle ergometer (Daum, premium 8i, Fürth, Germany). Resistance was then increased incrementally by 15 watts per minute until participants could no longer cycle above 60 rpm or achieve the American College of Sports Medicine (ACSM) recommendations for test termination [6]. Participants were considered to reach maximum effort if they achieved a respiratory exchange ratio of 1.10 or higher and a rating of perceived exertion (RPE, 6–20 scale) of 18 or higher on test termination [6,35,40,41].

2.4. Chronotropic Incompetence

The highest HR (HRmax) obtained during the CPET was used to identify CI, using the following chronotropic index equation: [(HRmax–HRrest)/(220–age–HRrest)]. HRrest, refers to the resting HR obtained from an averaged 10 s recording from the 12-lead electrocardiogram recorded in supine position. A chronotropic index below 0.8 was used to identify participants with CI [42,43].

2.5. Non-Contact Boxing Sessions

Two boxing sessions were randomized and performed at least two days apart. Before each session, a general warm-up of five minutes was performed on a stationary bike. Figure 1 illustrates the protocol used in the study, which was based on a HIIT protocol for people with PD that was shown to be feasible and effective [9]. Each session was divided into four rounds. Each round consisted of three high intensity bouts of 80 s with a 15 s rest period between bouts to introduce the next combination. Between rounds, participants were seated for two minutes. The rounds were performed on a boxing bag and using focus pads. Each boxing combination included footwork drills, including stance jumps/switch (skips) or squats (ducks) to simulate the defensive 'roll' movement. Consistent voice commands were used to prompt the boxing combinations (e.g., jab, cross, jab, rear hook) and to encourage participants to punch as fast and hard as possible throughout the rounds.

2.6. Outcomes

Maximum HR (HRmax) and average HR (HRavg) were measured during each boxing round. HRmax attained per round was then divided by the highest HR from CPET and multiplied by 100 to obtain HR as percentage of highest HR during CPET (%HR-CPET). A similar equation was used to obtain HR as percentage of maximum predicted HR (%MA-PHR). Tanaka's equation (207–0.7 * age) was used to estimate the MA-PHR for each participant [6].

HR at and above VT2 and 85% HRmax obtained from CPET were considered thresholds for high-intensity zones [44–47]. Thus, the percentage of time exercised in the high-intensity zone was calculated by summing each HR point $\geq$ VT2 and $\geq$ 85% HRmax. The time spent $\geq$ VT2 was divided by the duration of the rounds and multiplied by 100 for estimation of the amount of time at and above this threshold (HI-VT2). The same calculation was used to estimate the percentage of time ≥ 85% HRmax (HI-85%). At the end of each round, participants were asked to rate their perceived exertion using the 6–20 point RPE scale [40]. RPE is a common psychophysical measure of exercise intensity during activities such as boxing [20,48–50] and has been validated against physiological measures of exercise intensity in people with PD [51].

Average oxygen consumption (VO_2avg) relative to body weight (mL/kg/min) was measured during each round. VO_2avg was then divided by peak oxygen consumption (VO_2peak) and multiplied by 100 to obtain the average percentage of VO_2peak (%VO_2peak) per round. Total energy expenditure (EE) was calculated for the duration of the session. Each liter of oxygen consumption (VO_2) was approximated to generate 5 $kcal \cdot min^{-1}$ [52]. EE was estimated by multiplying absolute VO_2 (liter per minute) by 5, and then multiplying this figure by the total session duration in minutes. The result was expressed in kilocalories (Kcal).

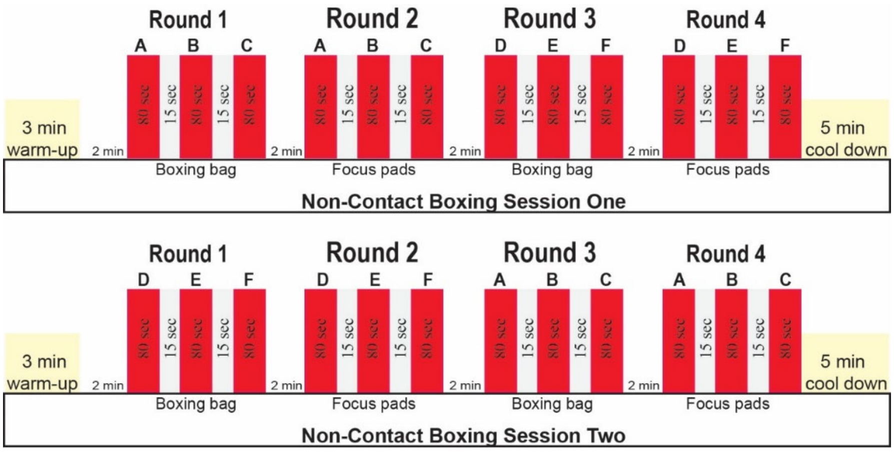

Figure 1. Each boxing round had a total duration of 4 min and 30 s, divided into three bouts of 80 s of boxing and 15 s of passive recovery (standing). During each round, participants were reminded of the following combinations. Combination A: jab, cross, jab, rear hook, 2x skip; Combination B: jab, jab, cross, lead hook, 4x skip; Combination C: jab, rear hook, jab, cross, 2x duck; Combination D: 4x jab, cross, 2x skip, 4x hook, 2x skip; Combination E: 4x jab, cross, 4x skip, 4x hook, 4x skip; Combination F: 4x jab, cross, 2x duck, 4x hook, 2x duck; The 2 min interval represents passive recovery (sitting).

2.7. Data Analysis

For demographic data, between-group differences (PD with (PDCI) and without CI (PD non-CI), and controls) were examined using analysis of variance (ANOVA) and post hoc tests (Tukey's HSD). For clinical data, between-group differences (PDCI and PD non-CI), time living with PD, levodopa equivalent (medication), and MDS-UPDRS were examined using t-tests, assuming equal variances and independent observations. These assumptions were examined using QQ plots, box plots, and histograms.

For CPET data, differences between groups were evaluated using linear regression models while adjusting for gender, age, height, time living with PD, levodopa equivalent, and body mass index (BMI). HR and metabolic data from boxing sessions were fitted for both completed and non-completed boxing rounds within the same linear mixed-effects model to account for repeated measures. However, model fit statistics were poor due to zero inflation which resulted in a non-normal distribution. To overcome this, we fitted models to the completed rounds only. Fixed effects included group, session, and rounds. Adjustments were made for the same covariates as the CPET data model, with the inclusion of VO_2peak (from CPET) as an additional covariate. The random effects (session and group) accounted for individual variability in the intercept across different sessions for each participant. Data were plotted to assess normality assumptions of residuals.

ANOVA was conducted to assess the significance of independent variables in regression models. Pairwise comparisons between different levels of the 'Group' factor were also conducted. For boxing data, comparisons were performed within each combination of 'round' and 'session'. Estimated means are reported with standard errors (SE) and 95% confidence intervals. The level of significance was set at $p \leq 0.05$. Data analysis was performed using R software (version 2024.12.0+467) for statistical computing [53].

Although this was an exploratory study, we estimated sample size prior to data collection with HRmax as the primary outcome. Using HRmax (PD 132 ± 20, control 158 ± 13) reported by Kanegusuku et al. [54] and CI prevalence data of around 40–50% [31,34], and taking $\alpha < 0.05$ with 80% power, a sample of 16 PD participants was required.

3. Results

Forty-five participants completed the CPET, including 28 people classified as having mild to moderate PD (Hoehn and Yahr (H&Y I-III) and 17 age-matched controls. Thirteen people with PD (46%) presented with CI. Two people with PD without CI requested to withdraw from boxing sessions due to personal reasons, and two with CI asked to stop boxing during the first round due to dizziness. Three control participants were excluded due to issues in collecting data ($n = 1$) and an inability to complete at least one full round due to the demanding intensity of the activity ($n = 2$).

Therefore, 11 PD participants with CI (PDCI), 13 without CI (PD non-CI), and 14 age-matched controls completed at least one full round (Table 1). PDCI participants completed 62 rounds of 76 possible (82%), PD non-CI participants completed 89 rounds of 96 (93%), and controls completed 103 rounds of 104 (99%). Rounds were not completed due to reported dizziness, or participants requested to stop due to the intense nature of the activity. Modifications in footwork were made in some sessions. The 'skip' movement was changed for 'duck' due to poor balance (PDCI ($n = 1$), PD non-CI ($n = 1$)) and sore calf muscles (PDCI $n = 1$). Sore knuckles were reported after the first boxing session by one control participant, who requested not to perform the second session.

Table 1. Demographic and clinical outcomes.

	PDCI ($n = 11$)	PD Non-CI ($n = 13$)	Control ($n = 14$)
Age; years	63.45 ± 6.36	62.31 ± 5.82	62.93 ± 6.38
Females (%)	2 (18%)	6 (46%)	6 (43%)
Height; cm	175.45 ± 7.19	170.73 ± 9.08	169.82 ± 6.42
Weight; Kg	87.91 ± 11.01 *†	69.08 ± 12.81	75 ± 12.36
BMI; Kg/m^2	28.64 ± 3.70 †	23.46 ± 3.41	25.79 ± 2.69
MoCA	25.27 ± 2.69	27.54 ± 2.30	26.50 ± 1.99
MDS-UPDRS part III	35.36 ± 6.87 †	27.15 ± 8.51	n/a
Years living with PD	6.62 ± 4.31	6.43 ± 4.06	n/a
Levodopa dose equivalent; mg/day	574 ± 455	605 ± 365	n/a

All values are in mean ± SD. BMI: body mass index; MoCA: Montreal Cognitive Assessment; MDS-UPDRS: Movement Disorder Society Unified Parkinson's Disease Rating Scale; * $p \leq 0.05$ vs. control; † $p \leq 0.05$ vs. PD non-CI.

3.1. Cardiopulmonary Exercise Test Outcomes

Table 2 summarizes the maximal and submaximal physiological measures obtained from the CPET. The HRmax, HR at VT2, and 85% HRmax were significantly lower for PDCI participants compared with PD non-CI participants and controls ($p \leq 0.001$), but were similar for PD non-CI participants and controls ($p \geq 0.05$). The VO_2peak and VO_2 at VT1 and VT2 were not significantly different between groups ($p \geq 0.05$).

Table 2. CPET maximal and submaximal physiological markers data.

	PDCI (n = 11)	PD Non-CI (n = 13)	Control (n = 14)
HRmax (bpm)	124 ± 3.42 [117, 131] *†	156 ± 3.01 [150, 163]	160 ± 3.16 [153, 166]
85% HRmax	105 ± 2.91 [99, 111] *†	133 ± 2.56 [128, 138]	136 ± 2.68 [130, 141]
HR at VT1 (bpm)	91 ± 3.80 [83, 99] *†	113 ± 3.34 [106, 120]	108 ± 3.50 [100, 115]
HR at VT2 (bpm)	114 ± 4.07 [106, 123] *†	144 ± 3.58 [136, 151]	143 ± 3.76 [135, 151]
VO_2peak (mL/kg/min)	24.4 ± 1.83 [21, 28]	28.1 ± 1.61 [25, 31]	29 ± 1.69 [26, 32]
VO_2 at VT1 (mL/kg/min)	14.6 ± 0.86 [13, 16]	15.7 ± 0.75 [14, 17]	15.7 ± 0.80 [14, 17]
VO_2 at VT2 (mL/kg/min)	22.2 ± 1.63 [19, 25]	25 ± 1.43 [22, 28]	25.2 ± 1.50 [22, 28]
Chronotropic index	0.65 ± 0.03 [0.58, 0.72] *†	0.99 ± 0.03 [0.93, 1.06]	1.02 ± 0.03 [0.95, 1.08]

All values are in mean ± SE [95% confidence interval]. HRmax: maximum heart rate obtained from the cardiopulmonary exercise test; HR: heart rate; VT1 and VT2: first and second ventilatory thresholds; VO_2peak: peak oxygen consumption. * $p \leq 0.05$ vs. control; † $p \leq 0.05$ vs. PD non-CI.

3.2. Non-Contact Boxing Training Outcomes

3.2.1. Heart Rate Responses

Table 3 summarizes HR responses during boxing sessions one and two. The HRavg, HRmax, and %MA-PHR during each round were significantly lower for PDCI participants than PD non-CI participants and controls during all rounds in both sessions ($p \leq 0.001$), but not between PD non-CI participants and controls ($p \geq 0.05$). The %HR-CPET was similar between groups across all rounds in both sessions ($p = 0.16$). Between sessions one and two, the HRavg ($p = 0.51$), HRmax ($p = 0.72$), %HR-CPET ($p = 0.76$), and percentage MA-PHR ($p = 0.72$) were not significantly different amongst all participants.

Table 3. Heart rate responses per round during the first and second boxing sessions.

	PDCI (n = 11)	PD Non-CI (n = 14)	Control (n = 14)
Average HR (bpm)			
Round 1 S1	101 ± 5.22 [90, 112] *†	134 ± 4.22 [126, 143]	140 ± 4.26 [132, 149]
Round 1 S2	106 ± 5.33 [95, 117] *†	135 ± 4.23 [127, 144]	143 ± 4.31 [134, 151]
Round 2 S1	107 ± 5.28 [96, 118] *†	141 ± 4.22 [133, 150]	147 ± 4.26 [139, 156]
Round 2 S2	112 ± 5.35 [101, 123] *†	141 ± 4.23 [133, 150]	147 ± 4.31 [138, 156]
Round 3 S1	114 ± 5.28 [103, 125] *†	146 ± 4.24 [138, 155]	154 ± 4.26 [145, 162]
Round 3 S2	117 ± 5.35 [106, 128] *†	146 ± 4.26 [137, 154]	150 ± 4.31 [141, 158]
Round 4 S1	116 ± 5.28 [105, 127] *†	147 ± 4.26 [139, 156]	153 ± 4.26 [144, 162]
Round 4 S2	118 ± 5.38 [107, 129] *†	147 ± 4.26 [138, 156]	152 ± 4.32 [143, 161]
Maximum HR (bpm)			
Round 1 S1	113 ± 5.10 [103, 124] *†	149 ± 4.10 [141, 157]	157 ± 4.13 [148, 165]
Round 1 S2	119 ± 5.37 [108, 130] *†	147 ± 4.26 [139, 156]	159 ± 4.33 [150, 167]
Round 2 S1	117 ± 5.16 [106, 127] *†	152 ± 4.10 [144, 160]	160 ± 4.13 [152, 169]
Round 2 S2	122 ± 5.40 [11, 133] *†	152 ± 4.26 [143, 161]	161 ± 4.33 [152, 170]
Round 3 S1	125 ± 5.16 [114, 135] *†	157 ± 4.12 [148, 165]	165 ± 4.13 [157, 174]
Round 3 S2	125 ± 5.40 [114, 136] *†	154 ± 4.29 [145, 163]	161 ± 4.33 [152, 169]
Round 4 S1	125 ± 5.16 [114, 135] *†	157 ± 4.15 [149, 165]	166 ± 4.13 [157, 174]
Round 4 S2	126 ± 5.43 [115, 137] *†	154 ± 4.29 [146, 163]	163 ± 4.35 [154, 171]
%HR-CPET			
Round 1 S1	90.0 ± 2.57 [85, 95]	95.2 ± 2.10 [91, 99]	99.1 ± 2.09 [95, 103]
Round 1 S2	94.6 ± 2.65 [89, 100]	94.1 ± 2.05 [90, 98]	100.4 ± 2.10 [96, 105]
Round 2 S1	92.7 ± 2.63 [87, 98]	97.4 ± 2.10 [93, 102]	101.4 ± 2.09 [97, 106]
Round 2 S2	96.7 ± 2.67 [91, 102]	97.1 ± 2.05 [93, 101]	102.0 ± 2.10 [98, 102]
Round 3 S1	98.7 ± 2.63 [93, 104]	100.4 ± 2.12 [96, 105]	104.6 ± 2.09 [100, 109]
Round 3 S2	98.9 ± 2.67 [93, 104]	98.3 ± 2.08 [94, 102]	101.5 ± 2.10 [97, 106]
Round 4 S1	99.0 ± 2.63 [94, 104]	100.6 ± 2.15 [96, 105]	104.9 ± 2.09 [101, 109]
Round 4 S2	99.6 ± 2.70 [94, 105]	98.7 ± 2.08 [94, 103]	102.8 ± 2.11 [97, 107]

Table 3. *Cont.*

	PDCI (*n* = 11)	PD Non-CI (*n* = 14)	Control (*n* = 14)
%MA-PHR			
Round 1 S1	69.6 ± 3.17 [63, 76] *†	91.5 ± 2.55 [83, 97]	96.3 ± 2.57 [91, 101]
Round 1 S2	73.2 ± 3.35 [66, 80] *†	90.5 ± 2.66 [85, 96]	97.6 ± 2.70 [92, 103]
Round 2 S1	71.7 ± 3.21 [65, 78] *†	93.5 ± 2.55 [88, 99]	98.5 ± 2.57 [93, 104]
Round 2 S2	74.9 ± 3.36 [68, 82] *†	93.3 ± 2.66 [88, 99]	99.2 ± 2.70 [94, 105]
Round 3 S1	76.3 ± 3.21 [70, 83] *†	96.3 ± 2.56 [91, 101]	101.7 ± 2.57 [96, 107]
Round 3 S2	76.5 ± 3.36 [70, 83] *†	94.5 ± 2.68 [89, 100]	98.9 ± 2.70 [93, 104]
Round 4 S1	76.6 ± 3.21 [70, 83] *†	96.5 ± 2.58 [91, 102]	101.9 ± 2.57 [98, 107]
Round 4 S2	77.1 ± 3.38 [70, 84] *†	94.8 ± 2.68 [89, 100]	100.1 ± 2.71 [94, 106]

All values are in mean ± SE [95% confidence interval]. HR: heart rate; bpm: beats per minute; %HR-CPET: heart rate as percentage of highest HR during CPET); %MA-PHR: heart rate as percentage of maximum predicted HR; * $p \leq 0.05$ vs. control; † $p \leq 0.05$ vs. PD non-CI; # $p \leq 0.05$ between sessions.

Figure 2 illustrates HR data from a single PDCI participant who completed four rounds of session one. Using the MA-PHR metric, he did not attain the high-intensity threshold (≥85% HRmax) for any of the boxing rounds. However, when the HRmax derived from the CPET was used, the high-intensity threshold was achieved in all four rounds.

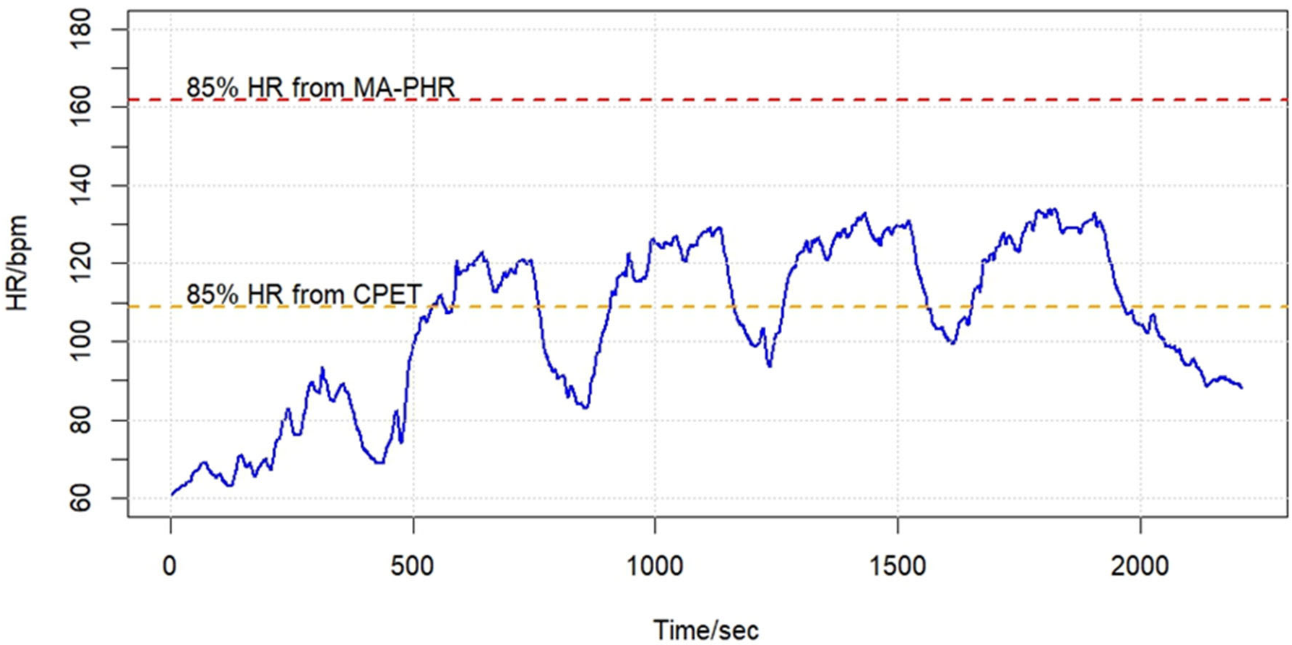

Figure 2. MA-PHR; maximum predicted heart rate. HR; heart rate; CPET; cardiopulmonary exercise test. MA-PHR was calculated using Tanaka's equation (207–0.7 * age) [6]. The participant's age was 65 years and the maximum HR during CPET was 128 bpm.

3.2.2. Percentage of Time Spent Above the Threshold for High-Intensity Training During Boxing

Table 4 summarizes the percentage of time spent above ≥85% HRmax from the CPET (HI-85%) and ≥VT2 (HI-VT2) in all rounds during both boxing sessions. HI-85% (p = 0.13) and HI-VT2 (p = 0.44) were not significantly different between boxing sessions one and two among all participants.

Table 4. Percentage of time exercised ≥ 85% HRmax (HI-85%) and ≥ VT2 (HI-VT2) for each round during the first and second boxing sessions.

	PDCI (*n* = 11)	**PD Non-CI (*n* = 14)**	**Control (*n* = 14)**
HI-85%			
Round 1 S1	43.6 ± 9.83 [24, 63] *	65.5 ± 8.06 [49, 82]	74.4 ± 7.98 [58, 90]
Round 1 S2	49.0 ± 9.25 [30, 68] *	66.3 ± 7.02 [52, 80]	85.8 ± 7.31 [52, 80]
Round 2 S1	52.0 ± 10.17 [32, 72] *	74.6 ± 8.06 [58, 91]	86.2 ± 7.94 [70, 102]
Round 2 S2	64.7 ± 9.35 [46, 84]	75.8 ± 7.02 [62, 90]	89.3 ± 7.39 [62, 90]
Round 3 S1	65.2 ± 10.17 [45, 86] *	84.0 ± 8.17 [68, 100]	93.9 ± 7.94 [78, 110]
Round 3 S2	80.8 ± 9.35 [62, 100]	80.5 ± 7.22 [66, 95]	87.5 ± 7.39 [66, 95]
Round 4 S1	71.4 ± 10.17 [51, 92]	83.5 ± 8.30 [69, 100]	90. ± 7.94 [74, 106]
Round 4 S2	84.4 ± 9.53 [62, 104]	81.6 ± 7.22 [67, 96]	96.7 ± 7.47 [82, 112]
HI-VT2			
Round 1 S1	13.0 ± 11.57 [−10, 36] *	37.0 ± 9.40 [18, 56]	59.4 ± 9.23 [41, 78]
Round 1 S2	27.2 ± 11.82 [3.4, 51] *	37.2 ± 8.98 [19, 55] *	70.8 ± 9.32 [52, 90]
Round 2 S1	29.1 ± 12.04 [4.9, 53] *	49.1 ± 9.40 [30, 68] *	78.1 ± 9.17 [60, 97]
Round 2 S2	42.3 ± 11.99 [18, 66]	52.5 ± 8.98 [34, 71]	75.5 ± 9.44 [57, 94]
Round 3 S1	53.7 ± 12.04 [29, 78] *	66.6 ± 9.57 [47, 86]	92.1 ± 9.17 [74, 111]
Round 3 S2	66.4 ± 11.99 [42, 90]	67.5 ± 9.24 [49, 86]	76.0 ± 9.44 [57, 95]
Round 4 S1	59.0 ± 12.04 [35, 83]	66.6 ± 9.77 [47, 86]	87.3 ± 9.17 [69, 106]
Round 4 S2	71.4 ± 12.24 [47, 96]	66.5 ± 9.24 [48, 85]	87.0 ± 9.55 [68, 106]

All values are in mean ± SE [95% confidence interval]. HI-85%: percentage of time spent at and above 85% of maximum heart rate obtained from the cardiopulmonary exercise test; HI-VT2: percentage of time spent at and above the second ventilatory threshold (VT2); * $p \leq 0.05$ vs. control; † $p \leq 0.05$ vs. PD non-CI; # $p \leq 0.05$ between sessions.

HI-85% was not significantly different between PDCI and PD non-CI participants ($p \geq 0.05$), or between PD non-CI participants and controls ($p \geq 0.05$) in both sessions. However, HI-85% was significantly lower in PDCI participants compared to controls during the first three rounds of session one ($p = 0.03$, $p = 0.01$, and $p = 0.04$), but not in the last round ($p = 0.18$). In the second session, HI-85% was significantly lower in PDCI participants than controls in the first round ($p = 0.007$), but not in the last three rounds ($p \geq 0.05$).

In session one, HI-VT2 was significantly lower in PDCI participants than controls in the first three rounds ($p = 0.006$, $p = 0.004$, and $p = 0.02$), but not in the last round ($p = 0.08$). Meanwhile, PD non-CI participants showed a significantly lower HI-VT2 only in the second round ($p = 0.04$) compared to controls, with no significant difference in the other rounds ($p \geq 0.05$). In the second boxing session, HI-VT2 was significantly lower in PDCI and PD non-CI participants compared to controls ($p = 0.01$ and $p = 0.01$) in the first round, but not in the other rounds of this session ($p \geq 0.05$).

3.2.3. Metabolic Responses

Table 5 shows that PDCI participants exhibited a significantly lower VO_2avg than controls in all rounds of both sessions ($p \leq 0.05$). In session one, PDCI participants also showed a significantly lower VO_2avg than PD non-CI participants in the first two rounds ($p = 0.024$, $p = 0.019$). PD non-CI participants showed a significantly lower VO_2avg than controls in the second and third rounds ($p = 0.043$, $p = 0.011$) of session one, and all rounds of session two ($p \leq 0.05$). The %VO_2peak was significantly lower in PDCI participants compared to controls across all rounds of session one and two ($p \leq 0.05$), but only in rounds one and two of session one when compared to PD non-CI participants ($p \leq 0.05$). PD non-CI participants showed a significantly lower %VO_2peak in rounds one, two, and three ($p \leq 0.05$), but not in round four ($p \geq 0.05$) of session one, and in all rounds of session two compared to controls ($p \leq 0.05$). The VO_2avg ($p = 0.71$) and %VO_2peak ($p = 0.67$) were not significantly different between boxing session one and two for all participants.

Table 5. Metabolic responses per rounds during the first and second boxing sessions.

	PDCI (n = 11)	**PD Non-CI (n = 14)**	**Control (n = 14)**
VO_2avg (mL/kg/min)			
Round 1 S1	19.3 ± 1.07 [17, 21] *†	22.5 ± 0.88 [21, 24]	25.1 ± 0.86 [23, 27]
Round 1 S2	20.7 ± 1.27 [18, 23] *	22.2 ± 0.98 [20, 24] *	26.0 ± 0.99 [24, 28]
Round 2 S1	19.5 ± 1.12 [17, 22] *†	22.9 ± 0.88 [21, 25] *	25.7 ± 0.86 [24, 27]
Round 2 S2	20.7 ± 1.29 [18, 23] *	22.2 ± 0.98 [20, 24] *	25.7 ± 0.99 [24, 28]
Round 3 S1	20.5 ± 1.12 [18, 23] *	23.0 ± 0.89 [21, 25] *	26.6 ± 0.86 [25, 28]
Round 3 S2	20.2 ± 1.29 [18, 23] *	21.6 ± 1.00 [20, 24] *	25.3 ± 0.99 [23, 27]
Round 4 S1	20.5 ± 1.12 [18, 23] *	22.2 ± 0.91 [20, 24]	24.2 ± 0.86 [22, 26]
Round 4 S2	19.6 ± 1.31 [17, 22] *	21.2 ± 1.00 [19, 23] *	24.8 ± 1.00 [23, 27]
% VO_2peak			
Round 1 S1	69.2 ± 3.84 [61, 77] *†	80.3 ± 3.11 [74, 86] *	91.1 ± 3.07 [85, 97]
Round 1 S2	74.5 ± 4.48 [65, 84] *	80.1 ± 3.47 [73, 87] *	93.6 ± 3.54 [86, 101]
Round 2 S1	70.7 ± 3.98 [62, 79] *†	82.1 ± 3.11 [76, 88] *	93.2 ± 3.07 [87, 99]
Round 2 S2	74.8 ± 4.54 [66, 84] *	80.2 ± 3.47 [73, 87] *	92.7 ± 3.54 [86, 100]
Round 3 S1	74.5 ± 3.98 [66, 82] *	82.1 ± 3.15 [76, 88] *	96.3 ± 3.07 [90, 102]
Round 3 S2	72.5 ± 4.54 [63, 82] *	77.7 ± 3.53 [70, 85] *	91.7 ± 3.54 [85, 99]
Round 4 S1	74.2 ± 3.98 [66, 82] *	79.3 ± 3.22 [73, 87]	88.3 ± 3.07 [82, 95]
Round 4 S2	70.3 ± 4.60 [61, 79] *	76.6 ± 3.53 [69, 84] *	89.4 ± 3.56 [82, 97]
	PDCI (n = 8)	PD non-CI (n = 11)	Control (n = 13)
Energy expenditure (kcal)			
Boxing session 1	196 ± 16.2 [162, 229] *	238 ± 14.7 [208, 269]	256 ± 13.1 [229, 283]
Boxing session 2	204 ± 16.4 [170, 237]	230 ± 14.4 [200, 259]	258 ± 13.2 [231, 286]

All values are in mean ± SE [95% confidence interval]. VO_2avg: average oxygen consumption per round; %VO_2peak: average oxygen consumption per round as percentage of peak oxygen consumption obtained from the cardiopulmonary exercise test. * $p \leq 0.05$ vs. control; † $p \leq 0.05$ vs. PD non-CI; # $p \leq 0.05$ between sessions. Energy expenditure (EE) refers to data of those participants who completed all four rounds during the sessions.

Three PDCI participants, three PD non-CI participants, and one control were unable to complete the four rounds of at least one session. Thus, their data were not included in the EE analysis (Table 5). In session one, the EE was significantly lower in PDCI participants than controls ($p = 0.03$), but not PD non-CI participants ($p = 0.12$). There was no difference between PD non-CI participants and controls ($p \geq 0.05$). During session two, the EE was similar between all groups ($p \geq 0.05$).

3.2.4. Ratings of Perceived Exertion (RPE) Responses

The RPE results indicate that PDCI participants perceived themselves to be exercising close to maximum effort despite having lower HR responses than PD non-CI participants and controls (Figure 3). In session one, the RPE was similar between all groups ($p \geq 0.05$), while in session two, PDCI participants reported a significantly higher RPE in rounds three and four ($p = 0.02$, $p = 0.01$) than the controls, and in round three compared to PD non-CI participants ($p = 0.03$). The RPE ($p = 0.90$) was not significantly different between boxing sessions one and two for all participants.

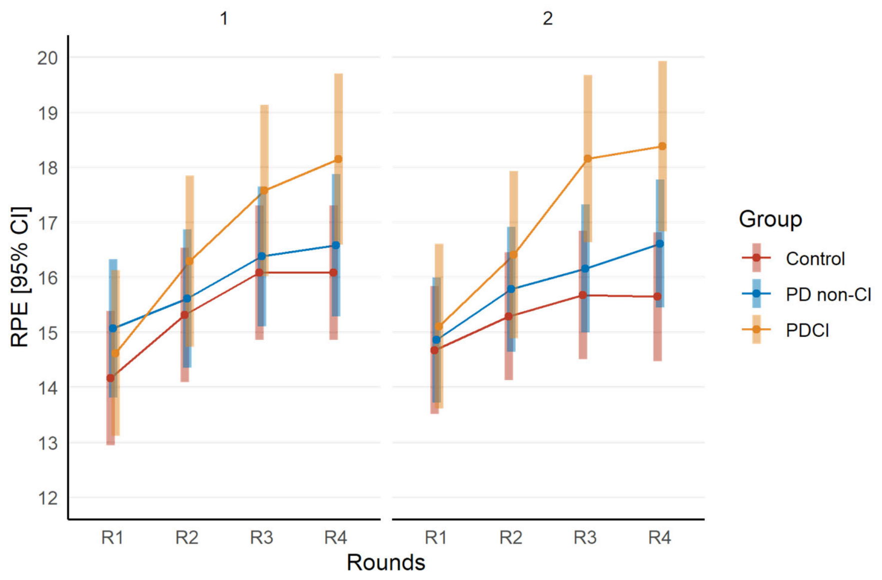

Figure 3. Mean (95% confidence intervals) rating of perceived exertion during the first and second boxing sessions.

4. Discussion

To our knowledge, this is the first study to demonstrate that boxing is a high-intensity exercise for people with PD with and without CI, based on individualized physiological profiles. Our results showed that the threshold for high-intensity exercise was attained despite the effect of CI on HR and metabolic outcomes during two boxing sessions. CI did not significantly lower the amount of time spent exercising at and above high-intensity threshold zones between PD groups, even though PDCI participants perceived that they were exercising harder than controls and PD non-CI participants. The study results also highlight that age-predicted equations underestimate exercise intensity in PDCI participants and should be used with caution.

When exercise intensity was calculated using Tanaka's equation to estimate HRmax [6], the PDCI group exercised at approximately 74% MA-PHR (moderate intensity) during boxing rounds. By comparison, PD non-CI participants trained at 93% and controls at 99% MA-PHR, respectively, representing a high-intensity training zone [55,56]. However, when the HRmax obtained from the CPET was used to calculate exercise intensity, all groups reached 90–105% of their individualized HRmax. These results highlight that age-predicted equations underestimate exercise intensity in the PDCI group and should be used with caution.

Exercise intensity in our study was higher than that reported for elite male and female athletes who exercise at approximately 80 to 95% of their individualized HRmax when sparring, simulating boxing matches, or training on boxing bags or focus pads [4,7,57]. The higher %HRmax achieved in our study compared to professional boxers may be due to the format of rounds, participants' fitness levels, and training specificity [6,58]. From a clinical perspective, our findings show that boxing is a high-intensity activity for PD with and without CI.

Most boxing interventions in people with PD provide little information on exercise intensity and only include boxing as a portion of their exercise intervention [1,3,15,16,18–21,55]. To the best of our knowledge, only one study has investigated HR responses during boxing in people with PD [50]. In a feasibility study, Blacker and colleagues included ten participants with PD in the early disease stage (H&Y I-II) during a 12-week boxing training program split into three training blocks of 4 weeks each [50]. Participants achieved the target exercise intensity of ≥80% of their MA-PHR, which was less than our PD non-CI participants (±93% MA-PHR).

The reasons for this may include an unknown number of participants with CI in their study compared with ours (participants were not categorized according to CI so this cannot be verified), or differences in the boxing protocol. For example, boxing rounds in the Blacker et al. study had a duration of 2–3 min each and were increased from six to eleven rounds per session during the 12-week exercise program. The authors used a Fightmaster unit with numbered pads for the boxing protocol, which also involved short bursts of punches (typically uppercuts lasting 10–15 s performed with maximal effort), loud upbeat music, and additional exercises such as star jumps [50]. By contrast, the boxing intervention in our study used equipment (punching bags and pads) typically available in community settings. In our study, the combinations and number of rounds were consistent, and although participants were asked to punch as fast and hard as possible, the punch rate and speed were self-selected. From a practical viewpoint, our data show that self-paced boxing training and standard boxing equipment could be used as an intervention to elicit high-intensity physiological responses in people with PD with and without CI.

The results from our study show that the percentage of time spent exercising at high intensity differed according to cutoffs. For example, PDCI participants spent about 47% of their exercise session time at or above VT2 and 64% at or above 85% HRmax obtained from the CPET. PD non-CI participants spent 54.5% and 76% of their session time at or above these intensity levels, respectively. The HR at VT2 represented approximately 90% of participants' HRmax.

Harvey et al. [9] used a similar protocol to our study, consisting of 4-minute intervals (45 s of exercise on a double-concentric resistance machine followed by 15 s of rest), interspersed with 3.5 min of recovery. They reported that their PD group (H&Y I–III) achieved high intensity (≥85% of HRmax) during 67% to 84% of their repetitions. This result is comparable to our PD non-CI group (76%), but higher than the PDCI group (64%). Harvey et al. [9] found a significant improvement in VO_2peak following the intervention and concluded that HIIT is feasible for people with PD and promising for improving aerobic capacity in this population.

In the current study, VO_2avg and %VO_2peak per round were significantly lower in both PD groups than in controls. While this difference can be partially explained by the presence of CI in the PDCI group, this does not expand to the PD non-CI group. Blunted HR in the PDCI group reduces cardiac output, which could significantly impact oxygen consumption [31,32,35,54,59]. Mitochondria dysfunction is another potential factor associated with reduced oxygen consumption in people with PD, which can reduce the arterio–venous oxygen difference by impairing the efficiency of oxygen extraction from the blood [6,54,60,61]. Despite having a lower metabolic response per round, people with PD exercised at approximately 72% (PDCI) and 80% (PD non-CI) of their VO_2peak, which, although lower than the control group (92%), is still higher than amateur boxers, who achieved around 66% VO_2peak during pad work [4]. The difference in VO_2 estimation methods, training protocols, participants' fitness levels, and training specificity may explain the variations in %VO_2peak observed between the two studies [4,6,58]. For example, our study collected metabolic data continuously throughout the boxing sessions, and combinations were not paced. In contrast, amateur boxers in the study by Arseneau and Mekary (4) were paced at a cadence of 180 beats per minute, with metabolic data collected only after the cessation of the final round.

The EE was significantly lower between the PDCI group and controls for session one, with a similar significant trend in session two. These findings suggest that PDCI participants may need to increase their training volume to meet the ACSM guideline of 1000 Kcal per week for health benefits and improvement in aerobic capacity [6]. Training volume adjustments may help compensate for the reduced energy expenditure of the

PDCI participants, which was approximately 40 to 50 Kcal per session compared to the PD non-CI group and controls. Participants from our study exercised for approximately 18 min (4 rounds of 4 min 30 s each), in which the EE per session was approximately 200 Kcal in the PDCI group, 234 Kcal in the PD non-CI group, and 257 kcal in controls. To achieve the ACSM recommendation, people with PD with CI would need to exercise for 90 min per week (11.11 kcal/per min), while people with PD without CI would need 77 min per week (13 kcal/per min), and controls 70 min per week (14.27 kcal/per min). The EE of our participants was similar to that of young males and females (9.8 and 11.2 Kcal/min), punching for 2 min during a six rounds of boxing [62].

The PDCI group displayed a significantly higher RPE than the PD non-CI and control groups in the later rounds of session two. The mean RPE for the PDCI group in rounds 3 and 4 was 18.2 and 18.4, which coincided with the higher percentage of time spent above 85% of HRmax in these rounds 2 (Table 4). Blacker et al. (50) reported an RPE of around 13–16 during their 12-week boxing exercise program, which is lower than in our study. This was probably due to different protocols and to the lower target HR that participants were required to achieve in the Blacker et al. study [50]. The RPE can be employed to monitor exercise intensity in individuals with CI. However, given its subjectivity, it is best utilized as a complementary tool alongside more objective measures of exercise intensity [6,35,63]. Our findings suggest that utilizing the RPE alongside HR monitoring may be a better approach for monitoring exercise intensity in people with PD when CPET data are unavailable.

5. Clinical Implications

- People with PD with CI achieved high-intensity thresholds during boxing sessions based on individualized measures but not on measures obtained from age-predicted equations.
- HR responses were significantly lower in people with PD with CI, while the RPE was similar or higher compared to those without CI.
- Age-predicted equations underestimate exercise intensity in people with PDCI and should be used with caution.
- Combining the RPE with HR monitoring can enhance the prescription of boxing exercises for people with PD with and without CI when individualized measures from CPET are not available [35].

6. Limitations

Although people with PD achieved a comparable %HRmax to controls, participants may not have punched at a similar speed or with comparable power, which may have influenced exercise intensity and EE [4,62,64–69]. Some participants with PD, as well as controls, reported previous boxing experience and, as a result, may have felt more confident when boxing. The findings reflect our current study protocol, and different bursts (rounds), recovery time and type (active or passive), and other training variables can influence physiological and clinical responses to boxing training [44–47]. Our study did not evaluate the improvement in aerobic performance to explore whether people with PD with and without CI showed similar improvements in VO_2peak after boxing training. Body weight was significantly higher in the PDCI group compared with the PD non-CI and control groups. BMI was included as a covariate in all models to account for the potential impact of body weight on outcomes. Although the main effects were non-significant, an undetected interaction may have influenced the findings [70,71]. Lastly, the small sample size and inclusion of people with PD with mild to moderate disease severity (H&Y I–III) limit the generalizability of our findings. Future research may consider using markerless video analysis to evaluate movement speed during boxing in people with PD. Studies with larger sample sizes are necessary to investigate the differences between individuals with PD with and without CI in the advanced stages of the disease. Additionally, exploring the effects of aerobic training, including boxing, on the VO_2max in individuals with PD with and without CI is warranted.

7. Conclusions

People with PD with and without CI attained high-intensity thresholds for aerobic training during two boxing sessions and spend significant time exercising at and above threshold zones. PDCI participants exhibited lower HR responses during boxing compared with PD non-CI participants and controls; however, when expressed as the %HRmax derived from CPET profiles, they exercised at a similar intensity. The RPE may be a useful clinical tool for measuring exercise intensity in conjunction with HR, and more informative than predictive equations, which may underestimate the HR response for people with PD.

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