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ORIGINAL RESEARCH

Heart rate response during a simulated Olympic boxing match is predominantly above ventilatory threshold 2: a cross sectional study

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Abstract: The present study aimed to describe heart rate (HR) responses during a simulated Olympic boxing match and examine physiological parameters of boxing athletes. Ten highly trained Olympic boxing athletes (six men and four women) performed a maximal graded exercise test on a motorized treadmill to determine maximal oxygen uptake ($52.2\ mL \cdot kg^{-1} \cdot min^{-1} \pm 7.2\ mL \cdot kg^{-1} \cdot min^{-1}$) and ventilatory thresholds 1 and 2. Ventilatory thresholds 1 and 2 were used to classify the intensity of exercise based on respective HR during a boxing match. In addition, oxygen uptake ($\dot{V}O_2$) was estimated during the match based on the HR response and the HR-$\dot{V}O_2$ relationship obtained from a maximal graded exercise test for each participant. On a separate day, participants performed a boxing match lasting three rounds, 2 minutes each, with a 1-minute recovery period between each round, during which HR was measured. In this context, HR and $\dot{V}O_2$ were above ventilatory threshold 2 during 219.8 seconds ± 67.4 seconds. There was an increase in HR and $\dot{V}O_2$ as a function of round (round 3 < round 2 < round 1, $P < 0.0001$).These findings may direct individual training programs for boxing practitioners and other athletes.

Keywords: heart rate, physiological profile, intermittent exercise, combat sports, boxing

Introduction

Boxing is a combat sport in which athletes try to strike and/or defend themselves from the attacks of their opponents. Matches are characterized by dynamic phases of short duration, which involve almost all muscle groups in complex movements characterized by short phases of maximal and/or supramaximal effort intensity, which lead to rapid accelerations and decelerations of body segments.[1]

To obtain an understanding of the physiological capacities underlying boxing performance, it would be useful to know the cardiovascular demand and the degree of recruitment of anaerobic metabolism during a match. These physiological variables would provide benchmarks for improving and monitoring athlete training regimens.[2,3] In addition, it could provide a basis for athletic performance strategies, as it would enable one to identify an athlete's potentials and limitations.[4] Heart rate (HR) monitoring offers the opportunity to directly and easily evaluate the physiological profile of discipline-specific performance and inexpensively evaluate the physiological demands.[5] However, few studies in the literature have reported on the physiological demands of combat sports.[1,6–9] In this context, maximal graded exercise testing is commonly employed to determine physiological response to exercise. Maximum oxygen uptake ($\dot{V}O_2$ max) of an individual, which serves as a good marker for aerobic fitness, can be achieved during an exhaustive exercise test. Furthermore, graded maximal exercise testing allows for the determination of ventilatory thresholds (first ventilatory threshold [VT_1] and second ventilatory threshold [VT_2]). VT_1 corresponds to the break point in the plot of carbon dioxide production ($\dot{V}CO_2$) as a function of oxygen uptake ($\dot{V}O_2$). At that point, the ventilatory equivalent for O_2 ($\dot{V}E/\dot{V}O_2$) increases without an increase in the ventilatory equivalent for CO_2 ($\dot{V}E/\dot{V}CO_2$). VT_2 is located between VT_1 and $\dot{V}O_2$ max, when $\dot{V}E/\dot{V}CO_2$ starts to increase as $\dot{V}E/\dot{V}O_2$ continues to increase. In practical terms, VT_1 and VT_2 can be used to prescribe exercise and to classify exercise intensity.

Because the popularity of combat sports practice is increasing,[6,10,11] research into the physiological profile of these sports is necessary. Therefore, the aims of this study were to investigate physiological parameters of amateur boxers and to describe HR responses during a simulated boxing match. Also, the study compared HR responses during a simulated boxing match with those of HR associated with VT_1 and VT_2 attained during a maximal graded exercise test.

Methods

Participants

Ten highly trained boxing athletes (six men [two junior and four senior] and four women [two junior and two senior]) were recruited from local boxing teams located in São Paulo, Brazil. The age and anthropometrical characteristics of the participants are presented in Table 1. Each participant's height and weight were measured to the nearest 0.1 cm and 0.1 kg, respectively. Skinfold thicknesses were obtained to estimate body fat percentage. Skinfold measurements were taken from seven sites on the right side of the body: triceps, subscapular, suprailiac, chest, abdomen, thigh, and midaxillary using a Lange skinfold caliper (Cambridge Scientific Industries, Inc, MD, USA). All skinfold measurements were carried out by the same examiner (to avoid inter examiner variability), who was previously trained and experienced in the use of skinfold calipers. Duplicate measurements were obtained, and the mean recorded value was used to determine body density.[12] The Jackson and Pollock equation[13] was used for male athletes, and the equation formulated by Jackson et al[14] was used for the female athletes. Body density values were then converted to body fat percentage using the Siri equations.[15]

Table 1 Characteristics of the boxing athletes

	Female athletes (n = 4)	Male athletes (n = 6)	Total (n = 10)
Age (years)	17.7 ± 1.7	18.0 ± 2.0	17. 9 ± 1.8
Height (cm)	164.3 ± 7.7	173.4 ± 7.5	169.7 ± 8.5
Body mass (kg)	61.2 ± 6.6	65.9 ± 12.2	64.0 ± 10.1
Body fat (%)	22.0 ± 3.5	12.7 ± 5.3	16.4 ± 6.5

Note: Data are presented as the means ± standard deviation.

All athletes trained five times a week in 2.5 hour sessions and had accumulated more than 2 years of training and competition. Their training focused on the development of technical and tactical skills that were specific to the sport of boxing and on the improvement of match-related fitness. All experimental procedures were approved by the University Human Research Ethics Committee and conformed to the principles outlined in the Declaration of Helsinki. All participants signed informed consent forms prior to participating in the study. For those participants under 18 years of age, written informed consent was signed by parents or guardians. All athletes were highly motivated to participate in the study and familiar with all testing methods. Participants continued their regular training programs and were requested, with their coaches consent, to refrain from strenuous workouts on the day before the test.

Baseline medical examinations

Before the beginning of the experimental procedures, each participant came to the laboratory for anamnesis and a physical examination to assess their health. These tests did not reveal any abnormalities that could contraindicate the participants' inclusion in the study.

Experimental procedures

Each participant reported to the laboratory on two separate occasions. During the first session, a maximal graded exercise test was administrated to determine VT_1, $VT_{2,}$ and $\dot{V}O_2$ max, as well as their associated running velocities and HR. In the second visit to the laboratory, the participants performed a simulated boxing match. A period of at least 48 hours separated the two laboratory visits, and all experimental procedures were completed within a 2-week period. All participants were instructed to refrain from eating 2 hours before laboratory visits and to abstain from caffeine, alcohol, and strenuous physical activity on each test day. Water intake was allowed ad libitum. The temperature and relative humidity in the testing laboratory ranged from 21°C–23°C and 55%–65%, respectively, for all trials. We carried out our experiments in both the morning and afternoon. However, for each participant, the maximal graded exercise test and simulated boxing match were conducted at the same time of day.

Prior to performing the maximal graded exercise test, participants were given a standardized set of instructions explaining the test. On completion of these preliminary procedures, each participant underwent an incremental maximal exercise test on a motorized treadmill (Super ATL, Inbrasport Ltd, São Geraldo, MG, Brazil) with 0% slope. The schedule of this test consisted of a 5-minute warm-up period at 6 $km \cdot h^{-1}$, and then the initial speed was adjusted to 7 $km \cdot h^{-1}$, followed by progressive increases of the treadmill speed at a rate of 1 $km \cdot h^{-1}$ every minute until participant exhaustion. During the exercise testing, participants were verbally encouraged to exercise for as long as possible. Respiratory gas samples of each breath were analyzed using a gas analyzer (K4b2, COSMED, Rome, Italy). Before each test, the gas analyzer was calibrated using gas of a known concentration (16% of O_2 and 4% of CO_2; White Martins, Rio de Janeiro, Brazil), and the flow meter was calibrated using a 3 L syringe (Hans Rudolph, Inc, Shawnee, KS, USA). A Polar Electronics HR monitor (Polar Electronics, FS1, Kempele, Oulu, Finland) was used to record in real-time, as the metabolic system utilized in this study was equipped with a receiver unit, able to capture the signal.

The following data (averaged over 20 seconds) were obtained: $\dot{V}O_2$ ($mL \cdot min^{-1}$) at standard temperature (0°C) and barometric pressure at sea level, $\dot{V}CO_2$ ($mL \cdot min^{-1}$) at standard temperature (0°C) and barometric pressure at sea level, respiratory exchange ratio (RER), minute ventilation $\dot{V}E$ ($L \cdot min^{-1}$) at body temperature and pressure saturated, respiratory rate (breaths per minute [bpm]), ventilatory equivalents for O_2 and CO_2 ($\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$, respectively), expired fractions of O_2 and CO_2 (%) and HR (beats per minute [bpm]). Peak treadmill velocity was defined as the last achieved running speed sustained for at least 30 seconds. $\dot{V}O_2$ max was always defined as the highest 20-second averaged $\dot{V}O_2$ value with inclusion criteria consistent with conventional guidelines for $\dot{V}O_2$ max (eg, an inability to sustain the workload, relative HR $>$95% predicted for their age, RER at maximal exercise $>$1.1, and $\dot{V}O_2$ plateau [the point at which $\dot{V}O_2$ increases less than 150 $mL \cdot min^{-1}$ for a given increase in workload]). Ventilatory thresholds were assessed using established criteria.[16] Briefly, VT_1 corresponds to the break point in the plot of $\dot{V}CO_2$ as a function of $\dot{V}O_2$. At that point, $\dot{V}E/\dot{V}O_2$ increases without an increase in $\dot{V}E/\dot{V}CO_2$. VT_2 was located between VT_1 and $\dot{V}O_2$ max, when $\dot{V}E/\dot{V}CO_2$ starts to increase and $\dot{V}E/\dot{V}O_2$ continues to increase. VT_1 and VT_2 were determined independently by three experienced investigators. If agreement between two out of three investigators was not achieved, VT was determined by consensus. To determine the $\dot{V}O_2$ and $\dot{V}E$ at VT_1 and VT_2, the average of the last 20 seconds of each corresponding level was used. In practical terms, ventilatory thresholds represent points that can be used to classify the intensity of aerobic exercise.

Finally, the second visit to the laboratory was used to apply a simulation of a boxing match. This simulation was conducted in a boxing ring (6 m × 6 m) and was accompanied by a referee with extensive experience in boxing. The participants were instructed to prepare themselves as they usually would for an official match. Participants performed a 10 minute warm up, which consisted of standard boxing movements, and then rested on a bench until HR returned to the pre-exercise level. The match consisted of three rounds, each 2 minutes long, with 1 minute of recovery between them. During each recovery period, the participant sat on a bench and was allowed to drink water. To simulate a match as realistically as possible, a sparring partner with a skilled trainer was enlisted. This partner had the same body mass, height, sex, ability, and boxing experience as the evaluated athlete and was aware of his or her participation in a scientific study. Additionally, the athletes were verbally encouraged by their coaches throughout the match to perform as well as possible. After the 1 minute recovery period following the last round, an additional 10 minute period of further recovery was allowed (final recovery). HR was recorded before, during (including rest periods between rounds), and after the simulated boxing match. HR registers (5-s average HR value) were monitored by a commercially available telemetric system (Suunto Team Pod, Suunto, Vantaa, Finland), which allowed us to monitor heart rate in real time. HR recorded during a simulated boxing match was compared with HRs corresponding to VT_1 and VT_2. In addition, $\dot{V}O_2$ was estimated during the match for each participant based on the HR response and the HR-$\dot{V}O_2$ relationship for each participant as determined from maximal graded exercise test results. Despite the indirect $\dot{V}O_2$ estimation by HR-$\dot{V}O_2$ relationship obtained from maximal graded exercise test, this strategy is considered valid for intermittent activities.[17–19]

Statistical analysis

All variables presented normal distributions ($P > 0.05$) according to Kolmogorov–Smirnov tests. Therefore, the differences between rounds were analyzed by one-way ANOVA (analysis of variance) for repeated measures. When significant modifications were found, the Tukey post hoc procedure was performed to localize the difference. Pearson linear regression analysis was used to determine any potential linear relationships between variables. All statistical analyses were performed with GraphPad Prism 5.0 (San Diego, CA, USA). The level of significance was $P < 0.05$. Data are shown as the means ± standard deviations.

Results

Data for the maximal graded exercise test are shown in Table 2. All participants (n = 10) attained age-predicted maximum HR, RER > 1.1, fatigue and $\dot{V}O_2$ plateau (when $\dot{V}O_2$ increased less than 150 mL · min^{-1} for a given increase in workload). The $\dot{V}O_2$ max of the athletes was 52.2 mL · kg^{-1} · min^{-1} ± 7.2 mL · kg^{-1} · min^{-1} and was reached at a treadmill speed of 15.7 km · h^{-1} ± 2.5 km · h^{-1}, with a maximum heart rate (HR_{max}) of 193 bpm ± 7 bpm. VT_1 and VT_2 were detected in all cases. The $\dot{V}O_2$ levels at VT_1 and VT_2 were 40.5 mL · kg^{-1} · min^{-1} ± 5.9 mL · kg^{-1} · min^{-1} and 47.5 mL · kg^{-1} · min^{-1} ± 6.0 mL · kg^{-1} · min^{-1}, respectively, and were reached at treadmill speeds of 11.0 km · h^{-1} ± 1.4 km · h^{-1} and 13.6 km · h^{-1} ± 1.8 km · h^{-1}, with HRs of 167 bpm ± 9 bpm and 181 bpm ± 6 bpm, respectively.

The HR behavior during the simulated boxing match is shown in Table 3. There was a round effect ($P < 0.0001$): the highest HR and percent of HR_{max} were attained in round three and were 4.7% ($P = 0.0008$) and 5.5% ($P = 0.0009$) higher than those attained in round one, respectively. The average HR in round two and percent of HR_{max} attained were both 4.5% ($P < 0.0001$ for both) higher than those attained in round one. The average HR in round three and the respective percent of HR_{max} attained were 6.3% and 5.5% ($P < 0.0001$ for both) higher than those obtained in round one, respectively. In round one, the average time spent at a HR below the VT_1 level was 22.5 seconds ± 23.9 seconds, time spent at a HR between the VT_1 and VT_2 levels was 47.9 seconds ± 35.5 seconds, and time spent at a HR above the VT_2 level was 49.6 seconds ± 42.7 seconds. In round two, the average time spent below the VT_1 HR was 9.0 seconds ± 7.5 seconds, between the VT_1 and VT_2 HRs was 21.0 seconds ± 7.8 seconds and above the VT_2 HR was 90.0 seconds ± 12.9 seconds. In round three, the mean time spent below the VT_1 HR was 7.0 seconds ± 16.0 seconds and 5.6 seconds ± 13.0 seconds, between the VT_1 and VT_2 was 14.0 ± 6.0 and above the VT_2 was 99.0 seconds ± 14.0 seconds. It is noteworthy that there was a progressive decrease in the amount of time below the VT_1 HR and, consequently, a gradual increase of the time spent above the VT_2 HR. Similar behavior was found in estimated $\dot{V}O_2$ during the simulated boxing match (Table 4).

There was a round effect for HR recovery ($P < 0.0001$): HR measured immediately at the end of the round was significantly different between rounds (Table 5) (round three > round two > round one). Regarding HR after 60 seconds of recovery, there was a significant difference only between round one and round two ($P = 0.0235$). HR recovery [Δ (%)] was 13%–19% for all rounds, without differences between them ($P = 0.1034$). In absolute values, the decrease in HR was 35 bpm ± 23 bpm, 26 bpm ± 11 bpm, and 32 bpm ± 13 bpm, respectively, for round one, round two, and round three, without differences between them ($P = 0.1229$).

There were no significant correlations between aerobic variables and Δ (%). $\dot{V}O_2$ max and its Δ (%) ($r = 0.5432$ and $P = 0.1047$), $\dot{V}O_2$ at VT_1 and its Δ (%) ($r = 0.5336$ and $P = 0.1122$), $\dot{V}O_2$ at VT_2 and its Δ (%) ($r = 0.6307$ and $P = 0.0506$), $\dot{V}O_2$ max and its Δ (%) ($r = 0.5227$ and $P = 0.1211$), VT_1 and its Δ (%) ($r = 0.5157$ and $P = 0.1271$) and VT_2 and its Δ (%) ($r = 0.5026$ and $P = 0.1387$) were all not correlated with HR recovery.

Table 2 Physiological parameter characterization obtained by graded exercise maximal test

	VT_1 (n = 10)	VT_2 (n = 10)	Maximal exercise (n = 10)
$\dot{V}O_2$(mL · kg^{-1} · min^{-1})	40.5 ± 5.9	47.5 ± 6.0	52.2 ± 7.2
% $\dot{V}O_2$ max	77.8 ± 6.8	91.3 ± 5.5	N/A
HR (bpm)	167 ± 9	181 ± 6	193 ± 7
% attained HR_{max}	86 ± 4	94 ± 3	N/A
Velocity (km · h^{-1})	11.0 ± 1.4	13.6 ± 1.8	15.7 ± 2.5

Note: Data are presented as the means ± standard deviation.
Abbreviations: bpm, beats per minute; HR, heart rate; HR_{max}, maximum heart rate; N/A, not applicable; $\dot{V}O_2$, oxygen uptake; VT, ventilator threshold.

Discussion

The primary aims of the present study were to describe the behavior of HR during a simulated Olympic boxing match and characterize the intensity of the modality and physiological profile of these athletes. The main finding of this descriptive study was that the average intensity of a simulated boxing match was very severe, as an appreciable percentage (~60%) of the exercise bout occurred at an intensity greater than VT_2, based on maximal HR (above 85% of the age-predicted maximal HR).

The findings of this study show that the percentage of the simulated boxing match at exercise intensities greater than VT_1 was much higher than routinely observed in athletes during spontaneous training,[20] although it is within the range of individual high-intensity training bouts in athletes.[21]

Wushu, Chito Ryu Seisan Kata, taekwondo, and Muay Thai are also combat sports that present elevated

Table 3 Heart rate and time (expressed as relative percentage) in each metabolic zone, defined as below VT_1, between the VT_1 and VT_2, and above the VT_2 during a simulated boxing match (n = 10)

	Round 1	Round 2	Effect size	Round 3	Effect size
Highest HR (bpm)	190 ± 8	194 ± 6	–	199 ± 5[a]	–0.56
% predicted HR_{max}	98 ± 4	101 ± 3	–	103 ± 2[a]	–0.62
Average HR (bpm)	175 ± 11	183 ± 6[a]	–0.41	186 ± 7[a]	–0.51
% attained HR_{max}	91 ± 5	95 ± 3[a]	–0.43	96 ± 2[a]	–0.55
Time below to HR at VT_1 (%)	19.0 ± 20.0	7.0 ± 6.0[a]	0.37	5.6 ± 13.0[a]	0.37
Time between to HR at VT_1 – VT_2 (%)	40.0 ± 30.0	18.0 ± 6.0[a]	0.45	11.6 ± 5.1[a]	0.55
Time above to HR at VT_2 (%)	41.0 ± 36.0	75.0 ± 11.0[a]	–0.54	82.8 ± 11.5[a]	–0.61

Notes: Data are presented as the means ± standard deviation. [a]Different from round 1 ($P < 0.05$). Effect size is a measure that describes the magnitude of the difference between two groups.
Abbreviations: bpm, beats per minute; HR, heart rate; HR_{max}, maximum heart rate; VT, ventilatory threshold.

intensities during matches.[4,22–25] Bridge et al[25] evaluated the HR responses of specific Taekwondo training activities practiced by experienced practitioners in a natural training environment and found that this sport stimulated the HR to reach 64.7%–81.4% of HR_{max}. Therefore, boxing, as with other combat sports, has a strong impact on cardiovascular and respiratory functions.

However, as an episodic training activity, the comparatively high intensity may be associated with an effective training response. In particular, results presented by Helgerud et al[26] and Laursen et al[27] have suggested that improving $\dot{V}O_2$ max in already trained athletes, required training intensities which approached the intensity of $\dot{V}O_2$ max. This could be a plausible explanation for the high $\dot{V}O_2$ max observed in our athletes. Other studies of boxing and various combat sports have found similar values of $\dot{V}O_2$ max.[7,11,22]

Another objective of the present study was to determine the aerobic physiological parameters of boxers. This is an important objective because the physiological profile is used to modify training programs and assist with individual competition strategies. For example, an athlete with a substantial maximal aerobic power (ie, high $\dot{V}O_2$ max) would be encouraged to maintain a high intensity of action during a match. On the other hand, an athlete with superior strength and anaerobic capacity might be more selective in the initiation of attacks[28] and be more explosive in the implementation of boxing actions. In this study, we found that athletes presented high $\dot{V}O_2$ max. In addition, the elevated% HR_{max} and%$\dot{V}O_2$ max attained during simulated boxing matches indicates that anaerobic complementation is important to this sport. Similar findings have been demonstrated previously for karate and taekwondo athletes.[7,24,29]

Reinforcing the importance of aerobic metabolism for performance in boxing, Guidetti et al[7] examined the relationship between ranking in boxing competition performance and some aerobic physiological parameters in eight middleweight-class elite Italian boxing athletes. A Spearman rho correlation analysis revealed that the $\dot{V}O_2$ at the individual anaerobic threshold ($46.0\ mL \cdot kg^{-1} \cdot min^{-1} \pm 4.2\ mL \cdot kg^{-1} \cdot min^{-1}$, $r = 0.91$) and the hand-grip strength (58.2 kg ± 6.9 kg, $r = 0.87$) were highly correlated ($P < 0.01$) with boxing competition ranking. $\dot{V}O_2$ max ($57.5\ mL \cdot kg^{-1} \cdot min^{-1} \pm 4.7\ mL \cdot kg^{-1} \cdot min^{-1}$, $r = 0.81$) and wrist girth (17.6 cm ± 0.6 cm, $r = 0.78$) were moderately ($P < 0.05$) correlated. These data suggest

Table 4 Estimated oxygen uptake and time (expressed as relative percentage) in each metabolic zone, defined as below VT_1, between the VT_1 and VT_2, and above the VT_2 during a simulated boxing match (n = 10)

	Round 1	Round 2	Effect size	Round 3	Effect size
Highest $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	50.8 ± 5.6	52.6 ± 5.2	–	54.6 ± 6.2[a]	–0.30
% attained $\dot{V}O_2$ max	99.3 ± 7.0	102.9 ± 5.7	–	106.6 ± 5.6[a]	–0.50
Average $\dot{V}O_2$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	44.2 ± 7.2	48.0 ± 6.1[a]	–0.27	49.6 ± 5.6[a]	–0.40
% attained $\dot{V}O_2$ max	86.9 ± 8.3	93.9 ± 5.1[a]	–0.45	97.0 ± 4.9[a]	–0.60
Time below to $\dot{V}O_2$ at VT_1 (%)	16.0 ± 13.9	7.3 ± 6.0[a]	0.37	3.5 ± 5.8[a]	0.50
Time between to $\dot{V}O_2$ at VT_1 – VT_2 (%)	51.7 ± 28.6	22.3 ± 9.9[a]	0.56	17.5 ± 9.7[a]	0.62
Time above to $\dot{V}O_2$ at VT_2 (%)	32.2 ± 34.1	70.4 ± 14.4[a]	–0.60	79.0 ± 14.0[a]	–0.66

Notes: Data are presented as the means ± standard deviation. [a]Different from Round 1 ($P < 0.05$). Effect size is a measure that describes the magnitude of the difference between two groups.
Abbreviations: $\dot{V}O_2$, oxygen uptake; VT, ventilatory threshold.

Table 5 Decrease in HR from 0–60 seconds after round as a percentage of HR measured immediately at the end of the round (n = 10)

	Round 1	Round 2	Effect size	Round 3	Effect size
HR_{0sec} (bpm)	187 ± 6	192 ± 5[a]	−0.41	195 ± 6[a,b]	−0.55/ −0.26
HR_{60sec} (bpm)	152 ± 25	166 ± 10[a]	−0.34	163 ± 14	–
Δ (%)	−18.8 ± 12.7	−13.3 ± 5.6	–	−16.4 ± 7.0	–

Notes: Data are presented as the means ± standard deviation. [a]Different from Round 1 ($P < 0.05$); [b]different from Round 2 ($P < 0.05$). Δ (%) was calculated as percentage of peak HR_{0sec}: $(HR_{60sec} - H_{0sec})/HR_{60sec} \times 100$. Effect size is a measure that describes the magnitude of the difference between two groups.
Abbreviations: bpm, beats per minute; HR, heart rate; HR_{0sec}, heart rate measured immediately at the end of the round; HR_{60sec}, heart rate measured after 60 seconds of recovery; $HR_{0sec} - HR_{60sec}$ (%), percentage of recovery between the end of the round and after 60 seconds of recovery.

that two basic factors are related to boxing performance: physical fitness, as indicated by individual anaerobic threshold and maximal oxygen uptake, and upper body muscular strength, as indicated by hand-grip strength (related to anaerobic metabolism).

Despite the development of lightweight, portable metabolic devices to measure physiological responses during an activity, one of the difficulties of working with boxing (and other combat sports) is measuring the $\dot{V}O_2$ during a match. Another reason $\dot{V}O_2$ was not measured in the current study was our intent to maintain the "ecological validity" of simulated matches. The term "ecological validity" in this setting refers specifically to the interaction of boxing athletes with their natural environment and practices.[25] Therefore, we estimated the $\dot{V}O_2$ during the simulated boxing match. We verified that $\dot{V}O_2$ attained during the matches reflected the high intensity of boxing, as mentioned above. Again, these results underscore the importance of a minimum of aerobic fitness for boxing athletes and suggest some guidelines for the intensity of training, in accordance with the literature.[8]

Increases in physiological variables ($\dot{V}O_2$ and HR) were observed over the course of the simulated boxing match and similarly in other intermittent sport activities. In addition, indirect $\dot{V}O_2$ estimation by HR-$\dot{V}O_2$ relationship is commonly considered acceptable for intermittent activities.[17–19] This indicates that there was a greater energy demand for the completion of high-intensity actions as sparing progressed. We suggest three factors that could be related to the increase in physiological demand during the match. First, athletes may have been under thermal stress due to protective garments. Second, the short rest periods between rounds (1 minute) did not allow sufficient time for physiological variables to decline. A third possibility is that each participant's competition strategy led to increased demand in each round. It is common for combat-sport athletes to save energy for the last period of the combat, when the most decisive attacks normally occur, resulting in an increase in the metabolic response during the last round.[24,30]

Finally, of particular interest in this study, was the ability of the athletes to recover their HR between rounds as analyzed through the relationships between aerobic variables ($\dot{V}O_2$ max, VT_1, and VT_2) and the decrease in HR. We found no correlations between these variables. There are two explanations for this: First, in martial arts environments, HR overestimations have been attributed to the static nature of upper and lower limb movements or only to upper limb movements (small muscle mass),[31,32] which seems plausible.[33] However, HR overestimations may also be attributed to emotional factors or thermal stress (as mentioned above). Together, these factors can contribute to a failure of HR to show appreciable recovery between work intervals.[34] Second, HR recovery following exercise is controlled by complex interactions between neural and humoral factors.[35] In this context, systemic stress metabolite accumulation during postexercise recovery (eg, plasma epinephrine, lactate, H^+, and inorganic phosphate)[36] might promote sympathetic activity via chemoreflex control of HR[37] and, consequently, delay HR recovery. Buchheit et al[38] compared the HR recovery response among children, adolescents, and adults, while also taking into account power output and the postexercise blood lactate concentration and acidosis. These authors showed that children experienced significantly faster HR recovery compared with their adolescent and adult counterparts. This apparent difference in HR recovery was associated with lower blood lactate and H^+ in children compared with adolescents and adults because children have an immature capacity for anaerobic metabolism.[38] Although the concentration of lactate was not measured in this study, it is likely that our volunteers presented a high concentration of this blood metabolite because, as mentioned earlier, this activity is of high intensity and therefore requires a significant anaerobic contribution.

Strengths and limitations of this study

First, our sample contained female and male participants. There are obvious differences in physiological and morphological characteristics between sexes (Table 1 and 2). For instance, women have a lower lung volume, cardiac output, $\dot{V}O_2$ max, and hemoglobin concentration as well as a greater body fat content compared to men.[39,40] However, there is evidence that physiological responses to exercise are not different between sexes, especially when HR, blood lactate, and percentage of $\dot{V}O_2$ max are analyzed during exercise.[3] Therefore, cardiovascular and metabolic strain seems to be comparable between sexes for the investigated situation in the present study.

Second, only ten participants were enrolled in the study due to the difficulty of recruiting elite boxers. Attaining high participant numbers is an inherent challenge in studies that involve a specific population, such as elite athletes. Other studies dealing with combat sports have employed participant numbers similar to our study or fewer.[3,4,24,29] Therefore, it is conceivable that the participants enrolled represent the typical amateur boxer.

Third, the fight was not recorded, so we were not able to assess movements performed by these boxers, such as high-intensity offensive and defensive techniques, the distance covered by the athletes, and work/rest ratios. These variables may interfere with HR responses during a fight.

Notwithstanding these limitations, this study demonstrates that boxing involves a high demand on the cardiovascular system and aerobic system, as evidenced by values of HR corresponding to vigorous and very vigorous exercise. The same can be said of the estimated $\dot{V}O_2$. Regarding whether aerobic fitness is an important determinant for the recovery of HR, this study found no statistically significant correlation between recovery of HR and $\dot{V}O_2$ max. It appears that in boxing, undertaking specific training to improve aerobic capacity seems to be necessary for the rapid recovery of HR between rounds. In summary, the present investigation provides baseline physiological data that can be used in the prescription of individual training programs for boxing athletes. These data are also important to coaches and can contribute to competition strategies for individual athletes and in individual matches. Furthermore, training protocols should include exercises that train both aerobic and anaerobic energy pathways, and amateur boxing could be used to develop aerobic fitness.

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Author contributions to this work were as follow: CABL and LFP-P: study concept and design, data acquisition, analysis, interpretation, and manuscript preparation; AAA and RLV: data analysis, interpretation, and manuscript preparation; MSA and RJFGF: data acquisition and critical revision of the manuscript; ACS: study concept and design, data analysis, interpretation, and critical revision of the manuscript. CABL and LFP-P contributed equally to this work and may be cited in interchangeable order.

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Disclosure

No commercial party having a direct financial interest in the results of the research presented in this article has or will confer a benefit upon the authors or upon any organization with which the authors are associated. There is no additional data available from this study. The authors report no conflicts of interest in this work.

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