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Strength and conditioning for combat sports athletes
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CHAPTER 1
Developing aerobic power and capacity for combat sports athletes

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Abstract
This chapter describes the physiological responses associated with aerobic power and capacity of combat sports athletes from different modalities (judo, Brazilian jiu-Jitsu, wrestling, Olympic boxing, taekwondo, karate and muay-thai) during specific and non-specific situations. Moreover, we describe the most used methods for the control and monitoring of these variables. Finally, the longitudinal studies that investigated the effects of aerobic power and capacity training for combat sports athletes are descripted.
Keywords: Martial arts; combat sports; aerobic fitness; training; performance; specific tests; high-intensity intermittent exercise; HIIT.

1. Introduction

Aerobic fitness involves two components: power and capacity. Aerobic power can be defined as the maximum rate at which oxygen can be used by the body during severe exercise [1]. In turn, aerobic capacity can be defined as the maximum amount of energy that can be generated by the oxidative system, that is, the highest effort intensity that can be maintained for long periods of time, being that above that intensity the measurement of oxygen consumption cannot be responsible for all the energy required to perform the exercise [2].

Combat sports can be characterized as intermittent modalities since there is the alternation of moments of effort and pause. In effort periods, the intensity of actions performed is alternated, although the quantification of this intensity is difficult to measure in the match itself [3]. The match duration in these modalities is varied and, frequently, a single match is divided in rounds [4,5,6,7]. Although the actions that define the outcome of the match are predominantly anaerobic [8], aerobic fitness is important because high values of this variable allow the athlete to maintain high intensities during match, since, they delay the fatigue process and facilitate recovery between the matches and between the effort periods of the same match [9]. In addition, there are studies demonstrating a temporal increase in the contribution of the oxidative system in a simulated match [4,5,10]. Taken together, these aspects demonstrate the importance of developing aerobic fitness to optimize performance during competitions. Considering the relevance of aerobic fitness, it is essential to know the responses related to oxidative metabolism in specific activities that are performed in training sessions. In fact, there are currently several studies that observed these responses (oxygen consumption and heart rate) in specific exercises [11], which can contribute to the better planning of training sessions and optimize the development of this fitness.

The aerobic fitness evaluation of combat sports athletes is usually performed in laboratory tests, conducted in ergometers [8,12,13], which do not meet the specificity of match actions; or in specific tests of the modalities [14-18]. In general, combat sports athletes present aerobic power and capacity values higher to those observed in the population [19]. When athletes of different competitive levels are compared, these values may be higher in athletes of higher level in taekwondo [20] and boxing [21], whereas for judo [8] and karate [13] this difference does not appear to occur.

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Therefore, the characterization of aerobic fitness levels of combat sports athletes accessed in both generic and specific tests is important in order to establish the relevance and expected levels of this capacity. In addition, periodic assessment of aerobic fitness can provide information that helps in monitoring and prescribing training sessions [8,13, 20]. Given this, the present chapter will first present the acute physiological responses (oxygen consumption [VO_2] and heart rate [HR]) in training situations, simulated matches, in official matches and in training sessions; specific tests for the evaluation of aerobic fitness in combat sports; and finally, longitudinal studies that analyzed the effects of training on the development of aerobic fitness of combat sports athletes, with possible inferences for the elaboration of the prescription of evidence-based training.

2. Cardiovascular responses and oxidative demands of combats

In the present topic, we will present the studies that measured HR and VO_2 responses. Considering that the measurement of VO_2 is an indication of the use of the oxidative system to resynthesize ATP and that during official match it is impossible to conduct this measure, some studies carried out this measurement in adapted situations to understanding the behavior of this variable in situations that are approaching of an official match [5,6,22]. Therefore, HR and VO_2 were analyzed in match performed in three different conditions: during training, simulating competition and in competition, in single and multiple matches.

Although HR and VO_2 are both markers of the demand for aerobic metabolism, VO_2 is the main marker, since it is a direct measure of the use of this metabolism. Unfortunately, it cannot be done in many situations. In addition, this measure requires expensive and sophisticated equipment for data collection. In the absence of VO_2 measurement, HR is used, however, this measure may provide misleading information on the request for oxidative metabolism in some situations, since it is only one of the components of the system involving aerobic metabolism.

VO_2 is the product of cardiac output multiplied by the arteriovenous O_2 difference (the difference between arterial and venous O_2 concentration) (Equation 1). In situations where there is an increase in energy demand, such as during exercise, the extraction of O_2 from the blood to the muscle is increased, decreasing the content of venous O_2. Thus, this decrease increases the arteriovenous difference due to the increase of VO_2 by the muscles. In turn, cardiac output is composed of the stroke volume multiplied by the HR (Equation 2).

VO_2 = Cardiac output X arteriovenous O_2 difference	**(Equation 1)**

Cardiac output = Stroke volume X heart rate	**(Equation 2)**

Therefore, in the impossibility of measuring the VO_2, HR has been used for decades as a marker of the intensity of aerobic exercise [23], although, as cited before, it represents only a part of the factors that determine the VO_2 and, consequently, the oxidative demand. In submaximal activities, HR and VO_2 exhibit linear behavior with increased of intensity. However, in intermittent high-intensity exercises, HR presents a distinct behavior of VO_2 [24]. In exercises above the velocity associated with VO_{2max}, HR response presents a delay in relation to the VO_2 response [25,26].

However, although some studies make adaptations to measure the VO_2, in some situations of combat (for example, jiu-jitsu) there is no possibility of measuring the VO_2 since in these gripping combat sports there is a great approximation between the athletes, which does not allow the use of the gas analyzer. In addition, this type of equipment has a high cost and is fragile, which makes it difficult to acquire by professionals involved in the training of athletes of these modalities. This is another reason why many researchers have also used HR as a marker of the aerobic system.

In addition, in some combat sports there may also be limitations for measuring HR during combat, often requiring interruption for conducted this measurement, or measurement only at the end of the match. Three forms have been used by researchers to access this measure: carotid palpation, use of monitor belt and use of electrocardiogram. The use of carotid palpation has a limitation on the data obtained, as it requires a few seconds (10 or 15s) to quantify the number of beats. In this period, the HR may already be declining, which may result in an underestimation of the value acquired. Therefore, when this type of method was used, it will be described in the text.

However, despite the limitations that exist in the use of HR during the match when the intensity does not exceed that associated with $VO_{2máx}$, the use of HR may, in fact, indicate the demand for aerobic metabolism. However, coaches should be cautious when using HR response in the match to the prescription of aerobic training because there is no linearity of the HR and VO_2 responses in exercises above the velocity associated with $VO_{2máx}$. In addition, factors such as cardiovascular deviation contribute to the dissociation of the relationship between HR and VO_2 in situations in which exercise is prolonged [27].

Finally, the studies that estimated the relative contribution of the oxidative system to energy transfer in combat sports will be presented. This information will be presented separately for the gripping, followed by the striking combat sports. Some studies have estimated the contribution of the three energy systems in simulated matches or training sessions [for example, 4,5,6]. For these estimates, it is necessary to measure VO_2 throughout and 6 min after the match, as well as blood lactate before and 1, 3, and 5 min after the match to calculate the delta of lactate (peak lactate minus the lactate concentration at rest). Briefly, the oxidative energy system contribution is represented by averaged VO_2 during the simulated match but subtracting resting VO_2 considering a fixed caloric quotient of 20.92 kJ per liter of oxygen. Subsequently, the total energy expenditure is calculated as the sum of the three energy systems. Relative oxidative energy system is expressed as a percentage in relation to total energy expenditure.

To facilitate the understanding of cardiovascular responses in single or multiple, simulated or official (competition) situations, a table will be presented at the end of the text of each modality in order to respond punctually to the following questions:

1) Are there studies describing how HR and VO_2?
2) What are the mean values HR and VO_2 in a match?
3) What are the values of the post-match HR and VO_2?
4) In a single match, is there an increase in the values of the pre-match HR and VO_2?
5) In a single match, but fragmenting the total duration of combat, is there an increase in HR and VO_2 values? At what point does this increase occur? Is there a progressive increase in these values?
6) Mean and peak HR and VO_2 values during combat, represent what percentage of the anaerobic thresholds of these variables?
7) Mean and peak HR and VO_2 values during combat, represent what percentage of the maximal values of these variables?
8) In a single match, is there a difference between the values of the simulated combats and the official matches?
9) In multiple matches, whether simulated or official, is there a distinct HR and VO_2 response?

2.1. Grappling combat sports

2.1.1. Judo

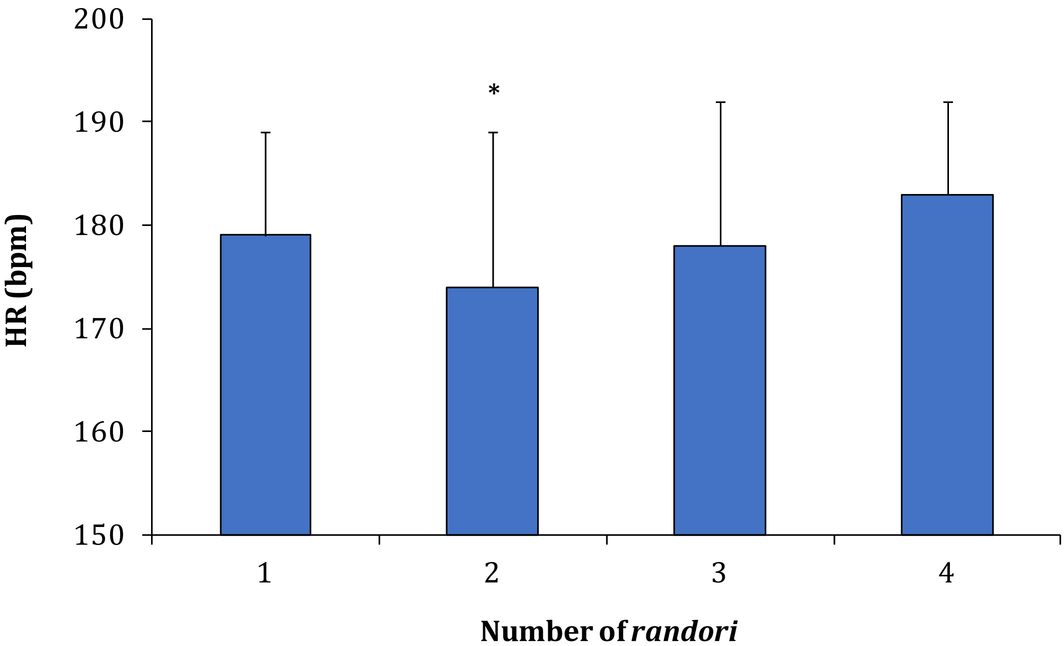
Kaneko, Iwata, and Tomioka [22] analyzed the VO_2 of five judo athletes in two different training situations, including *randori* (a match conducted during the training sessions on a continuous basis and without the intervention of a referee to apply the rules, mainly to establish pause periods). In the first situation, the athletes evaluated performed ten 4-min *randori* with ten different opponents. VO_2 was also measured at other times during the training session: 10-min before and after warm-up, 5-min of warm-up, and 30-min after the end of the *randori*. In the second situation, the VO_2 was measured in five 4-min *randori*, but interspersed with a pause period of the same duration. In this situation, VO_2 was also measured at other times of the experimental session: 10-min before and after warm-up, 1-min of warm-up that was a *randori* and 30-min after the end of the *randori*. The measurements of the VO_2 were possible in these situations, as one of the researchers held the equipment that carried out the analysis of the gases (Douglas bag) and followed the movement of the athlete being evaluated. The *randori* were performed only in the standing position since it is impossible to do these measures during the groundwork combat. As a result, the authors noted that the solicitation of the oxidative system is lower in the intermittent *randori* (~29.40 ml.kg-

^{1}.min^{-1}) compared to the continuous *randori* (~30.89 ml.kg^{-1}.min^{-1}). Possibly, in pause periods, the anaerobic systems contributed in a more pronounced way to perform the efforts during the *randori* in intermittent compared to the continuous condition.

Subsequently, Ahmaidi et al. [28] used a portable gas analyzer to measure VO_2 in eight physically active men while performing simulations of judo match or kendo match. The techniques used were performed with some restrictions, imposed due to the use of the equipment. Although the participants were not high-level athletes, this study provides relevant information to understand the behavior of VO_2 over time. When the values were expressed in relation to the VO_{2max} value measured in a cycle ergometer test for lower limbs, the authors observed, for moments 1-, 2- and 3-min, values of 28, 68 and 78% of $VO_{2máx}$, respectively. These data, although limited by the characteristics of the sample, demonstrate that it is probable that there is an increase in the demand of oxidative metabolism during the match to supply the necessary energy, since the substrates stock of the ATP-PCr metabolism is limited and there is accumulation of metabolites resulting from the glycolitic metabolism [29] and may not be replenished or removed during match due to the fact that the pause periods are short.

During an official judo match is prohibited wear monitor that measure HR. Thus, some studies that aimed understand HR response in a judo match performed this measure during a *randori* [30] and in simulated matches [31]. Ahmaidi et al. [28] also measured HR in the experimental protocol, besides VO_2, and they verified an increase of values over 3-min simulated match, being mean HR values from third (166 ± 18 bpm) and second minute (161 ± 18 bpm) higher than first minute values (130 ± 22 bpm).

Ten national and international athletes performed four 5-min *randori* interspersed by 1-min passive recovery period with the same duration [30]. In this study, there are two important limitations that must be considered when the HR response is observed. R*andori* was performed continuously and it was not intermittent as in official competition because it is observed lesser occurrence and duration of recovery periods. As it was not established pause periods by the referee, this way of match results in inferior time than real duration and, possibility this difference in dynamic of the match occasion modifications as physiological responses observed. Moreover, the recovery period had the same duration of the match, that does not follow the rules to offer at minimum a recovery equivalent to two matches duration. As results, authors observed that mean HR were approximately 170-180 bpm. Moreover, second *randori* values were lower than third *randori* values, without any difference to the first and fourth *randori* (Figure 1).



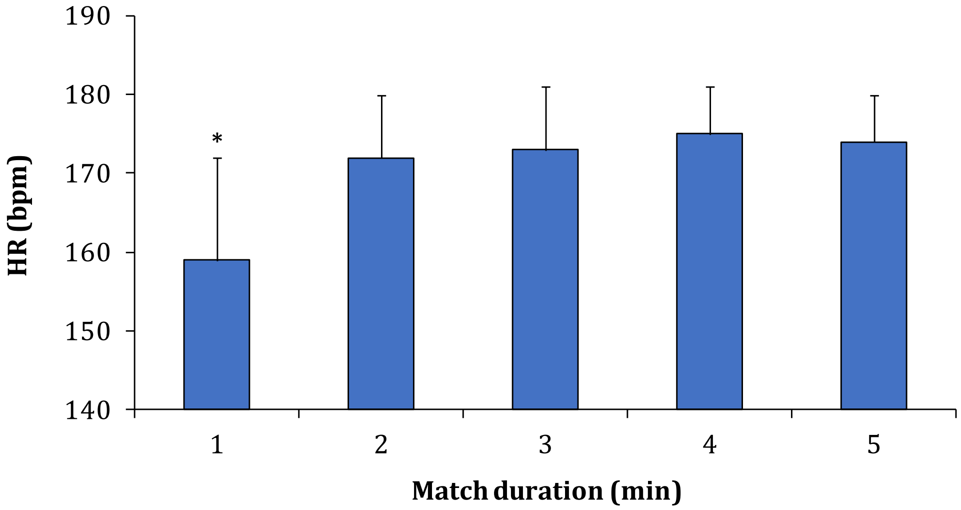
* = different from third *randori* ($p < 0.05$).

Figure 1: Heart rate response at the end of four 5-min *randori* interspersed by 5-min pause (Adapted from Branco et al. [30]).

Considering that *randori* is developed in a continuous way it seems that HR values are similar to simulated matches that are characterized by intermittence. Sanchis et al. [32] evaluated 26 athletes in a simulated judo match with a mean duration of 173s measuring HR by carotid palpation during 30s. In this study, probably, the match was finalized when there was *ippon*. To calculate maximum HR in the match authors utilized an equation considering values from post-match in 35, 60 and 120s. Values calculated were 172 ± 16 bpm and these values were not correlated with match duration or blood lactate.

Sbriccoli et al. [33] measured HR from six Olympic athletes on the Italian team during a 5-min simulated match. Each match was realized with two different opponents each one for each half match aiming to maintain high-intensity during the match. Measurements were realized during and after each match (15-20-min). Including the pause periods, the match mean duration was around 7-min and maximum HR values were 180 ± 11 bpm, representing 95% of maximal value obtained in treadmill maximal incremental test. During the match, the authors observed a marked increase of HR in the first 90s seconds, with a more discreet increase until the end of the match. Moreover, it was observed that HR was not reduced during pause periods. After 12-min, approximately, values measured were equivalents to 60% of HR_{max} (measured in treadmill maximal incremental test).

Aiming to understand the time course of some physiological variables modification over the match, including HR, Julio et al. [34] evaluated 10 judo athletes in five simulated matches with different durations (1, 2, 3, 4 and 5-min) with order random determined, with the same partner, in different days and blinded duration of match to athlete, in others words, the athlete did not know the match duration and they were instructed to consider that always match duration would be 5-min duration. The authors observed that HR values differed between different durations, being 1-min match values lower than values observed in other durations (Figure 2). These data show a stabilization of HR after the second minute of the match.



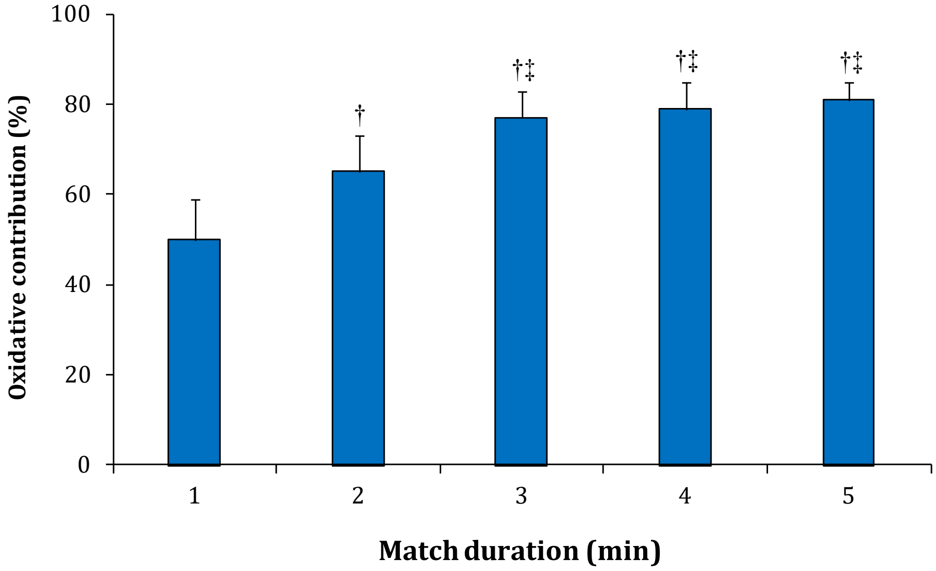
* = different from longer matches duration ($p < 0.05$).

Figure 2: Heart rate response in simulated matches with different durations (Adapted from Julio et al. [34]).

Kim et al. [31] did not observe modifications in HR values after simulated match performed against two different opponents (each one for each half of the match) after four and eight weeks of high-intensity intermittent training. Lack of modifications in HR values was observed as in the group that trained (TG) as in the control group (CG), although these modifications have been observed in anaerobic performance. Measurements were realized before the beginning of the training period (CG: 177 ± 9 bpm; TG: 172 ± 7 bpm), after four weeks of training (CG: 176 ± 8 bpm; TG: 173 ± 6 bpm) and after eight weeks of training (GC: 175 ± 7 bpm; TG: 172 ± 7 bpm).

Julio et al. [35] estimated the contribution of three energy systems to simulated judo matches in twelve judo athletes (18 ± 1 years-old, 175.1 ± 5.3 cm, 74.3 ± 10.5 kg). Each athlete was evaluated in five combats with different durations (1, 2, 3, 4 and 5-min), against the same opponent and blinded to the duration. The results demonstrated an increase in the oxidative system (from 50% to 81%), a decrease in ATP-PCr (from 40% to 12%) and maintenance of the glycolytic contributions (between

6% and 10%). Therefore, the oxidative system was the predominant system to supply the energy cost of judo matches from the first minute of combat up to the end when compared to the anaerobic systems (Figure 3).



† = different from 1-min; ‡ = different from 2-min ($p < 0.05$, in all comparisons).

Figure 3: Estimated relative oxidative system contribution in judo matches of different durations (values are mean ± SD) (Adapted from Julio et al. [35]).

Table 1: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in judo.

	HR	VO_2
Are there studies describing these variables?	Yes	Yes
Are there mean values during the match?	Yes	Yes
Are there post-match values?	Yes	NS
In a single match, is there an increase in pre-match values?	Yes	Yes
In a single match, but fragmenting the total duration of match, is there an increase in values?	Yes	NS
At what point does this increase occur?	1st min	NS
Is there a progressive increase in these values?	Yes, until 2nd min	NS
Mean and post-match values represent what percentage of the maximum values of these variables?	Mean 78%	Mean 95%
Mean and peak values during match, represent what percentage of the anaerobic thresholds of these variables?	NS	NS
In a single match, is there a difference between the values of the simulated matches and the real matches?	NS	NS
In multiple matches, simulated or official, is there a different response?	NS	NS

NS = no studies were found investigating this variable.

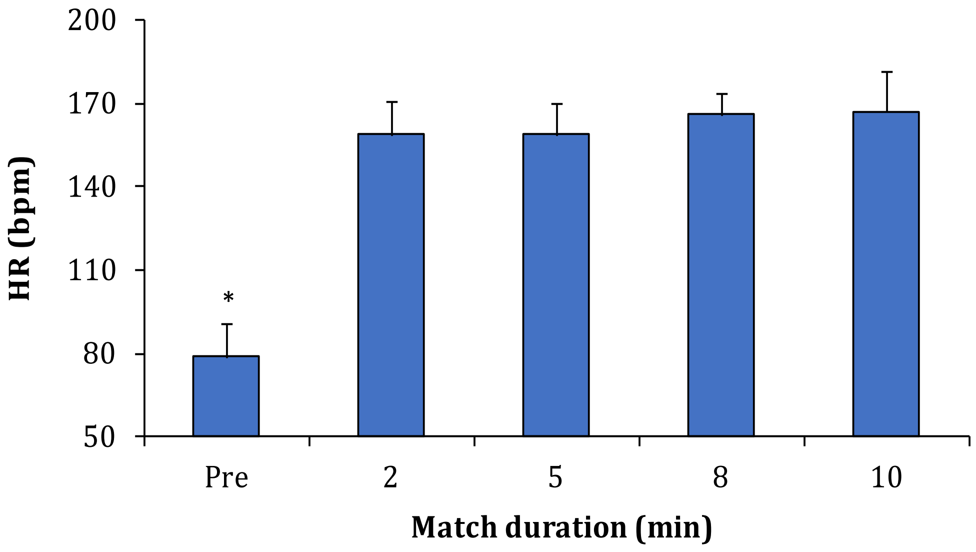
2.1.2. Jiu-Jitsu

Andreato et al. [36] compared HR responses of 12 athletes from different competitive levels in a continuous match, without referee interruption during four moments: resting, after warm-up, immediately and 14-min post the end of the match. The authors observed that resting values (80 ± 13 bpm) were lower than further values, as well as post-warm-up values (122 ± 25 bpm) and post-recovery (107 ± 19 bpm) were lower than post-match values (165 ± 17 bpm). These results even tough limited by the continuous characteristic of the simulated match, demonstrate that HR show an increase after the warm-up period, however, this increase is inferior to increase observed after the end of the match, and presents a decrement in the values when it is measured after a two times match duration recovery period.

To infer the solicitation of aerobic metabolism during jiu-jitsu match, Franchini et al. [37] submitted 22 athletes to 5-min match. At the final of each minute of the match, the evaluator measured HR (maximum of 30s to measure HR). The authors observed that HR values in the first minute (~148 ± 15 bpm) were not different at the second minute (~153 ± 16 bpm), but they were lower than third (~161 ± 17 bpm), fourth (~157 ± 15 bpm) and fifth minute of the match (~166 ± 16 bpm). Moreover, HR at the end of the fifth minute was higher than values observed in the second and fourth minute of the match. Even though Franchini et al. [37] study has been the first to investigate HR measurements over the match, it is necessary to consider the limitations of this method considering the insertion of pause periods longer than during an official competition, which likely allowed a higher recovery for the athletes.

In a similar experimental design from Franchini et al. [37], eight athletes were submitted to 10-min match, with HR being measured each 2-min [38]. With greater match duration time of HR measurement, it was observed that values at 8 (~168 ± 8 bpm) and 10-min matches values (~168 ±6 bpm) were higher than 2-min match values (~160 ± 12 bpm). However, the limitation of this study is the same as those of Franchini et al. [37] study. Thus, it would be more accurate understand HR time course a study that fragment 10-min match.

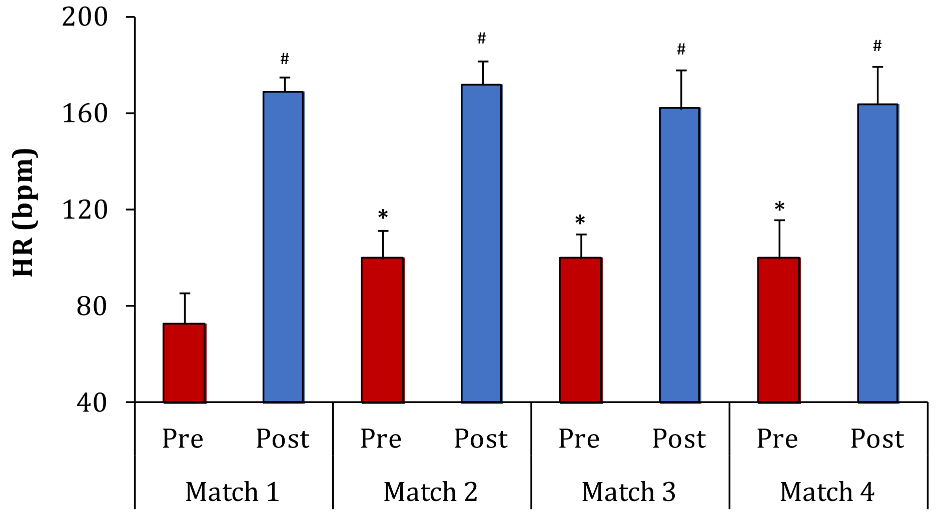
Two studies were performed to understand HR time course during the match [39] and during simulated competition (four matches in the same day) [40]. In Andreato et al. [39], 10 jiu-jitsu athletes, brown and black belt, were submitted to four matches with different match durations (2, 5, 8 and 10-min), performed in two different days, with the same opponent, with the random order determined, being each day performed two conditions (2 match duration) separated by 60-min recovery interval. Athletes did not know match duration, it was blinded, they always started math considering 10-min match duration. The evaluator stopped the match according to the duration previously determined for that day. This strategy was adopted to avoid the athletes from modifying the intensity of effort according to the total duration of the match. HR was measured before and after the end of each match. The authors observed differences between all post-match values compared than pre-match values (Figure 4), demonstrating stabilization of this variable over the match. A limitation of this study was the minimal match duration that was 2-min. In Judo, Julio et al. [34] observed that at 1-min match values were lower than de 2, 3, 4 and 5-min matches values. Thus, if the minimum duration in Andreato [39] study was 1-min, maybe differences could be observed as well.



* = different from post-matches values ($p < 0.05$).

Figure 4: Heart rate response in simulated matches with different durations (Adapted from Andreato [5]).

Andreato et al. [40] evaluated 10 Jiu-Jitsu athletes, brown and black belt, in four 10-min matches interspersed by a 20-min recovery period (simulating Jiu-Jitsu competition). During recovery periods there was a passive resting, but it was conducted also tests to evaluate performance and were done blood draws. HR was measured before and after each match. The authors observed differences between all pre-match values compared with all post-match values, as well as differences between pre-first match values compared with pre from further matches values (Figure 5).



* = different from pre-match 1 values ($p < 0.05$); # = different from pre-match values ($p < 0.05$).

Figure 5: Heart rate response before and after four 10-min jiu-jitsu matches in simulated competition (Adapted from ANDREATO et al. [40]).

Table 2: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in jiu-jitsu.

	HR	**VO_2**
Are there studies describing these variables?	Yes	No
Are there mean values during the match?	No	NS
Are there post-match values?'	Yes	NS
In a single match, is there an increase in pre-match values?	Yes	NS
In a single match, but fragmenting the total duration of match, is there an increase in values?	Yes	NS
At what point does this increase occur?	2nd min	NS
Is there a progressive increase in these values?	No	NS
Mean and post-match values represent what percentage of the maximum values of these variables?	NS	NS
Mean and peak values during match, represent what percentage of the anaerobic thresholds of these variables?	NS	NS
In a single match, is there a difference between the values of the simulated matches and the real matches?	NS	NS
In multiple matches, simulated or official, is there a different response?	No	NS

NS = no studies were found investigating this variable.

2.1.3. Wrestling

As observed in jiu-jitsu, the aerobic metabolism solicitation to energy transfer during wrestling match also was quantified by HR, but a lesser number of studies and with less details can be found compared with modalities already above described. HR has been measured during a simulated competition, in a freestyle (5 matches in two days) [66], and Greco-roman style (5 matches in a unique day) [41] and in a single match [42,43].

Considering HR response during a single wrestling match Greco-Roman style, Theophilos et al. [43] submitted 12 Greek athletes (under 74 kg) to a simulated match composed by three 2-min rounds. During the whole match, HR was registered and results are presented in Figure 6. The authors observed that HR round 1 mean values were lower than rounds 2 and 3 mean values.

In turn, Karninčić, Baić, and Sertić [42] evaluated eight athletes from the national Croatia team represented each one from eight categories were evaluated in two times: 1) at the beginning of first competitive period (12/2007) and at the final of the competitive period (03/2008). The match was composed of three 2-min rounds with a 30-s pause between rounds. HR was measured to estimate the intensity of work done. Although investigators did not have compared HR values between the competitive periods neither between rounds, this study brought HR information (Figure

7), being possible to infer that HR is elevated during the match compared to pre-match values, as well as possible lack of difference values measured in different time.

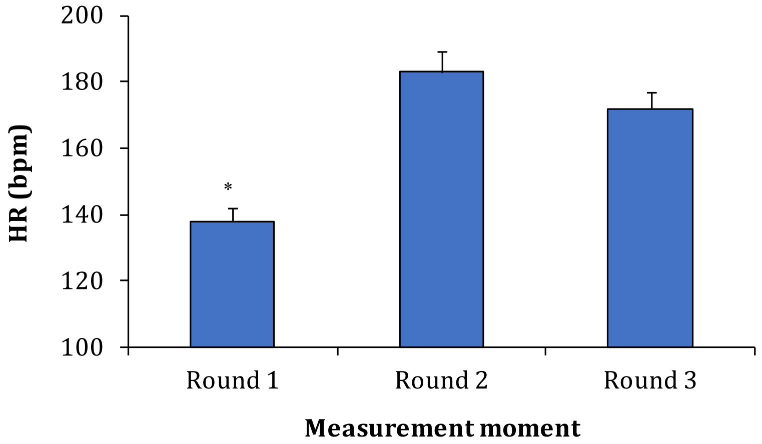


Figure 6: Heart rate response in different time of measurements during simulated Greco-Roman wrestling match composed of three 2-min rounds (Adapted from Theophilos et al. [43]).

* = different from round 1 ($p < 0.05$).

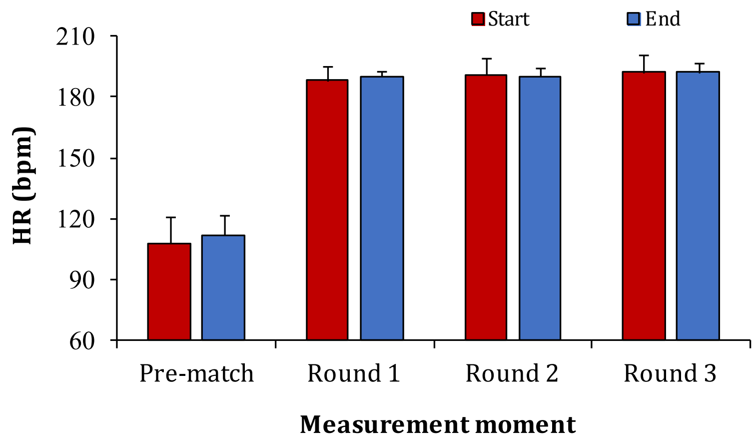
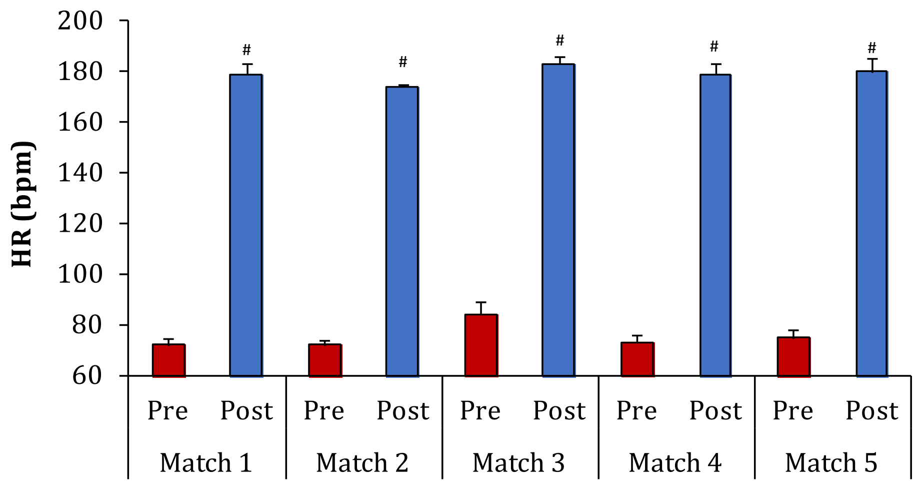


Figure 7: Heart rate response in different times of measurements during simulated Greco-Roman wrestling match composed by three 2-min rounds interspersed by 30s interval, in the beginning and at the end of a competitive period (Adapted from Karninčić, Baić and Sertić [42]).

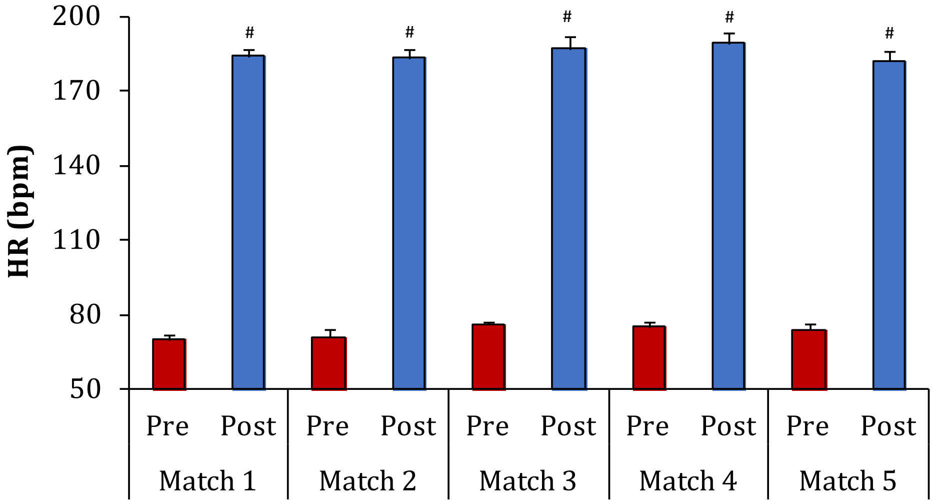
Kraemer et al. [44] submitted 12 freestyle wrestlers to a simulated competition over two days (simulating competition at that period). Athletes were submitted to a 6% body mass reduction in a week (range between 4.6 and 6.8%), being allowed a 2% tolerance in the second day of competition. On the first day, three matches were conducted and in the second day, two matches. All matches lasted 5-min. HR measurements were performed before and after each match by carotid palpation during 15s. The pre-match values did not differ from baseline values measured before the body mass reduction period and all post-values were higher than pre-match values, without any difference between the matches (Figure 8).



= different from pre-match values ($p < 0.05$).

Figure 8: Heart rate response before and after five 10-min freestyle wrestling matches simulated competition (Adapted from Kraemer et al. [44]).

With a similar experimental design used by Kramer et al. [44], including reduction of body mass in the week before the execution of the study, Barbas et al. [41] submitted 12 competitive wrestlers, to a simulated one-day Greco-Roman wrestling tournament. Each one of five matches was composed of three 2-min rounds interspersed by a 30-s pause. HR was measured during the whole match and registered in 5-s intervals. Thus, the authors compared pre and post-match values, as well as mean and peak values of each match. The authors verified that all post-match values were higher than pre-match values, without any difference between the matches (Figure 9). There was no difference between mean and peak values across the matches. Additionally, HR mean values, HR post-match and HR_{peak} represented, respectively, 83-86%, 92-96% and 96-98% of maximal values of these variables obtained in the maximal incremental test.



= different from pre-match values ($p < 0.05$).

Figure 9: Heart rate response before and after five Greco-Roman wrestling matches composed of three 2-min rounds interspersed by 30s pause between rounds, simulating a one-day tournament (Adapted from Barbas et al. [41]).

Table 3: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in wrestling.

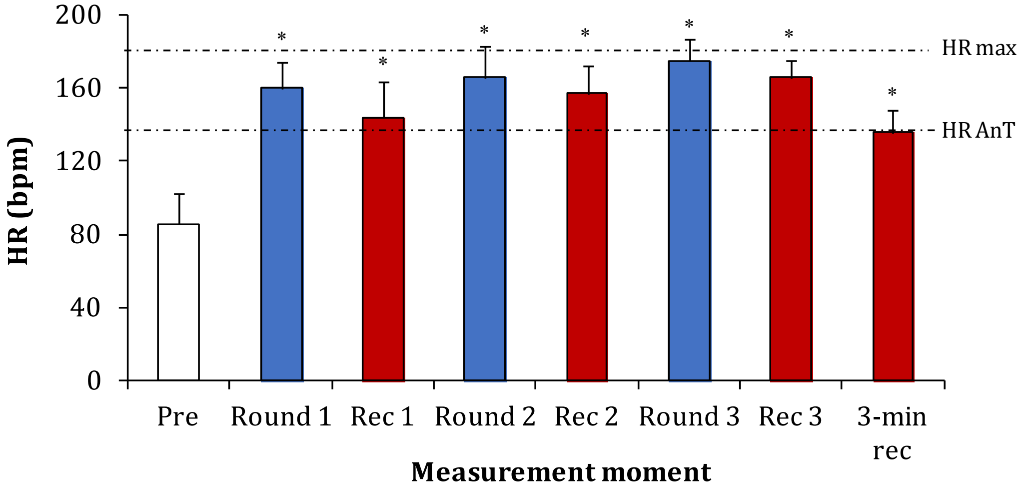
	HR	**VO_2**
Are there studies describing these variables?	Yes	No
Are there mean values during the match?	Yes	NS
Are there post-match values?	Yes	NS
In a single match, is there an increase in pre-match values?	Yes	NS
In a single match, but fragmenting the total duration of match, is there an increase in values?	Yes	NS
At what point does this increase occur?	1° round	NS
Is there a progressive increase in these values?	No	NS
Mean and post-match values represent what percentage of the maximum values of these variables?	83-86% 92-96%	NS NS
Mean and peak values during match, represent what percentage of the anaerobic thresholds of these variables?	NA	NS
In a single match, is there a difference between the values of the simulated matches and the real matches?	NA	NS
In multiple matches, simulated or official, is there a different response?	No	NS

NS = no studies were found investigating this variable.

2.2. Striking combat sports

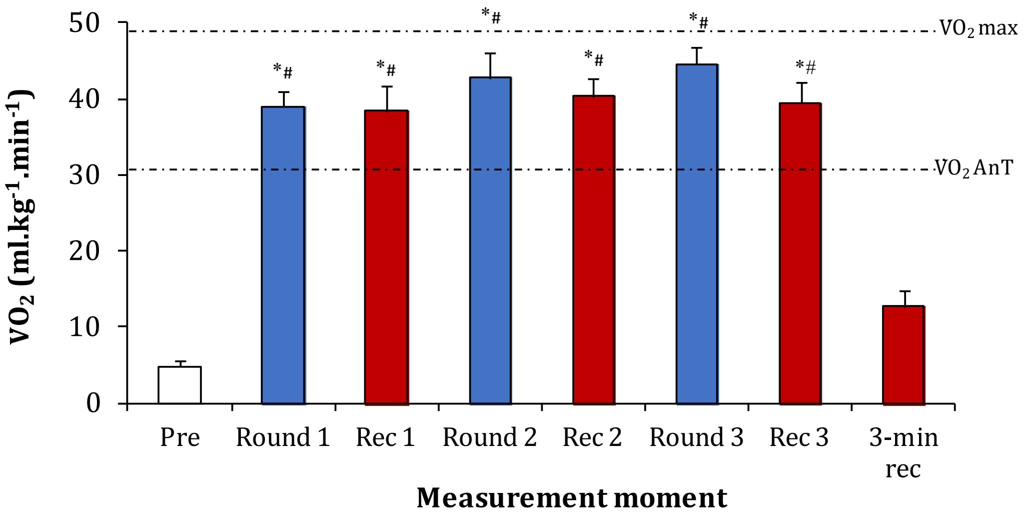
2.2.1 Muay-Thai

Crisafulli et al. [6] submitted 10 athletes to a simulated match composed of three rounds with 3-min duration and interspersed by 1-min recovery. Each round was composed by one set of six attacks and six defenses. At the end of the simulated match, the athletes were asked about the similarity of demand of this match compared with a real match, and they obtained an average score of 4 in a range of 0 to 5 (between any similarity and very similar, respectively). HR and VO_2 were monitored during and 3-min after the end of the match. The authors verified that HR increased in recovery periods between rounds and at the end of the match when compared to rest values. Moreover, HR values during the match and recovery periods remained above HR values related to the anaerobic threshold obtained in a treadmill maximal incremental test (Figure 10). In a similar way, the same time course was observed to VO_2, with values measured during the match being above those related to the anaerobic threshold and higher than the rest values. Moreover, there was no difference in VO_2 values between the effort and recovery periods, with the exception to the post-match recovery period, because these values did not differ from resting values (Figure 11) [6]. HR and VO_2 values represented approximately 92% and 86% from their respective maximal indexes.



rec = recovery; HR_{max} = maximal heart rate values obtained in the maximal incremental test; HRAnT = heart rate value at the anaerobic threshold obtained in the maximal incremental test; * = different from pre-match values ($p < 0.05$).

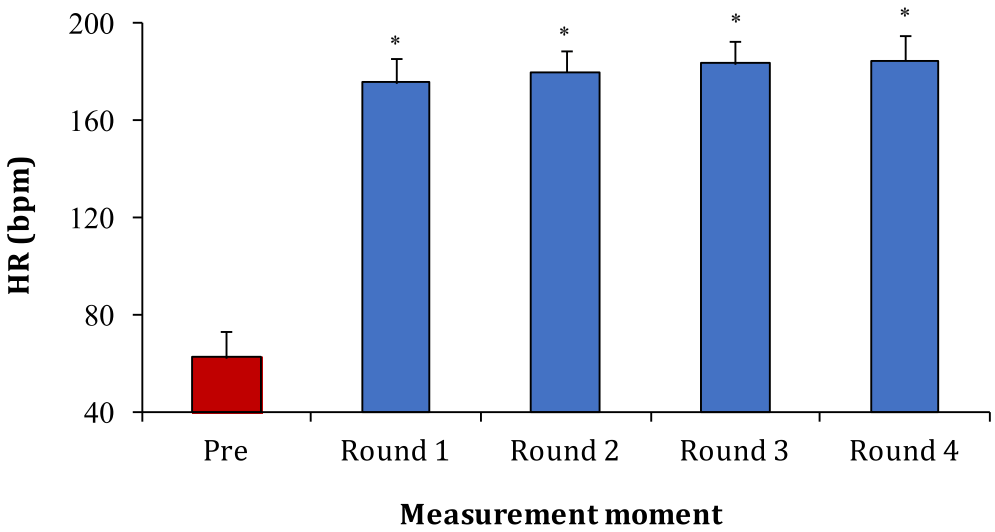
Figure 10: Heart rate response during different time points of a muay-thai simulated match (three 2-min rounds interspersed by 30s interval) and after 3-min recovery (Adapted from Crisafulli et al. [6]).



rec = recovery; VO_{2max} = maximal oxygen consumption obtained in maximal incremental test; VO_2AnT = oxygen consumption value at the anaerobic threshold obtained in the maximal incremental test; * = different from pre-match values ($p < 0.05$); # different from final recovery ($p < 0.05$).

Figure 11: Oxygen consumption response during different time points of muay-thai simulated match (three 2-min rounds interspersed by 30s) and after 3-min recovery (Adapted from Crisafulli et al. [6]).

The comparison of HR values during muay-thai simulated match was analyzed by Cappai et al. [45], including a comparison between winners and losers. In this study, 20 national and international level athletes performed a match composed of four 2-min rounds, interspersed by 1-min recovery. HR was measured in five-time points: at resting and at the end of each one of four rounds. As expected, HR values after the match were higher than rest values (Figure 12). HR mean values were 179 ± 0 bpm, being these values higher than values associated with anaerobic threshold obtained in treadmill maximal incremental test. Additionally, authors did not observe differences in HR values between winners and losers.



HR = heart rate; * = different from pre-match values ($p < 0.05$).

Figure 12: Heart rate response in rest and during four rounds of muay-thai simulated match, interspersed by 1-min interval between round (Adapted from Cappai et al. [45]).

Table 4: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in muay-thai.

	HR	**VO_2**
Are there studies describing these variables?	Yes	Yes
Are there mean values during the match?	Yes	Yes
Are there post-match values?	No	No
In a single match, is there an increase in pre-match values?	Yes	Yes
In a single match, but fragmenting the total duration of match, is there an increase in values?	Yes	Yes
At what point does this increase occur?	1° round	1° round
Is there a progressive increase in these values?	No	No
Mean and post-match values represent what percentage of the maximum values of these variables?	Mean 92%	Mean 86%
Mean and peak values during match, represent what percentage of the anaerobic thresholds of these variables?	Above	Above
In a single match, is there a difference between the values of the simulated matches and the real matches?	NS	NS
In multiple matches, simulated or official, is there a different response?	NS	NS

NS = no studies were found investigating this variable.

2.2.2. Karate

Studies investigating karate, beyond analysis HR and VO_2 responses, two of them tried to estimate the contribution of the three energy systems to supply the energy cost. Beneke et al. [4] evaluated 10 karate athletes from national and international ranking *kumite* matches (between two and four matches) aiming to compare the contribution of the three energy systems to supply the energy cost, being aerobic contribution estimated by VO_2 above rest values, caloric equivalent, and body mass. The authors estimate the contribution of the three energy systems in 36 matches with mean duration of 267 ± 61s and with effort and pause ratio of 2:1 (18s and 9s, respectively). Recovery interval between matches was determined according to that was observed during the national competition in the year that this study was conducted: between first and second matches, recovery interval was 17 ± 2-min; between second and third matches, 15 ± 1-min; and between third and fourth, 9 ± 1-min. The results demonstrated energetic cost had an average of approximately 335 kJ, being oxidative system responsible by greater relative contribution (%). In addition, VO_2 values (41.3 ± 13.1 $ml.kg^{-1}.min^{-1}$) and relative aerobic contribution (78 ± 6%) were similar between matches.

Doria et al. [10] also aimed to investigate the contribution of the three energy systems to supply the energy cost in the match, however without referee interference. Moreover, the authors performed these measurements during the *kata* (oppositions movements sequence) using the method of Beneke et al. [4]. The sample was composed by 12 Italian athletes, with six men and six women, which one were subdivided in the group that performed the *kumite* and groups that performed the *kata*. Each group was composed of 3 athletes with this sample size a limitation of the study. Above all, considering only results from match male group (duration of 240s) it was verified similar results to that observed by Beneke et al. [4], proving predominance of aerobic metabolism to transfer energy in this type of match. The energetic cost was approximately 305 kJ, with aerobic metabolism predominance (70%) and HR peak of 175 ± 5 bpm. In addition, the authors observed that aerobic contribution male group was higher than female group during the match and higher than the male group in which athletes reached HR_{max} about 191 ± 4 bpm and VO_{2max} about 48.5 ± 6.0 $ml.kg^{-1}.min^{-1}$, the VO_2 average was 34.9 ± 3.0 $ml.kg^{-1}.min^{-1}$ corresponding to 72% of VO_{2max}.

Iide et al. [46] submitted three adults partners karate athletes (18 – 20 years old) and 3 young partners (16-17 years-old), to 2-min simulated match followed by 3-min simulated match and analyzed VO_2 and HR. A treadmill maximal incremental test to obtain VO_{2max} was conducted as well and VO_2 and HR equivalent to anaerobic threshold were calculated. In the maximal incremental test, the athletes showed VO_{2max} of 51.2 ± 4.3 $ml.kg^{-1}.min^{-1}$; HR_{max} of 188 ± 2 bpm and the anaerobic threshold was 66.5 ± 7.0 % VO_{2max}. During 2-min match, HR values (160 ± 13), % HR_{max} (85 ± 7) and %VO_{2max} (42 ± 10) were lower than observed in 3-min match (170 ± 9 bpm; 93 ± 4% HR_{max} and 47.8 ± 8.0 %VO_{2max}). VO_2 during 2 and 3-min match remained below VO_2 associated anaerobic threshold.

Tabben et al. [47] evaluated seven winning karate athletes (4 men and 3 women) in three matches into an international competition and HR values were registered during the match (5s periods); and also, in treadmill maximal incremental test (maximal values reached in the test). The matches duration was 5.4 ± 1.5 min in men 3.6 ± 1.0 min in females. Recovery intervals between matches were: 33.6 ± 7.6-min between first and second matches; and 14.5 ± 3.1 min between second and third matches. The HR was analyzed each 5s and time spent in specific intensity zones. Mean values are presented in Table 6. The HR remained most of the time between 90 and 100% of HR_{max}, whereas time (%) in each zone did not differ between matches. The authors also did not detect changes in match total time duration, HR and %HR mean values.

Table 5: Absolute (bpm) and relative (% HR maximal) heart rate of winning athletes in three matches into an international karate competition (Adapted from Tabben et al. [47]).

		HR (bpm)	HR (% of HR maximal)
Match 1	Males	177 ± 9	88 ± 3
	Females	185 ± 11	92 ± 3
	All	181 ± 10	90 ± 3
Match 2	Males	179 ± 7	89 ± 4
	Females	185 ± 10	92 ± 3
	All	182 ± 8	91 ± 4
Match 3	Males	181 ± 8	90 ± 2
	Females	185 ± 9	92 ± 2
	All	183 ± 8	91 ± 3
Mean	Males	179 ± 7	89 ± 3
	Females	185 ± 9	92 ± 2
	All	182 ± 9	91± 3

Comparison of HR response in simulated and competitive matches was conducted by Chaabéne et al. [48]. For that, 10 international level karate athletes were evaluated in two situations (simulated and official) interspersed by two weeks interval. HR was measured in 5s intervals and, posteriorly calculated the mean and peak values of each condition. Above all, from ten athletes that performed the procedures, it was only possible to analyze data from 3 athletes in the simulated match and six athletes in competitive match, because HR acquisition was only possible in these athletes. The authors did not observe difference in mean and peak HR values, between simulated and official matches (Figure 13), and % HR_{max} was 92%. However, the comparison between these data was limited by sample size. It is important to highlight some interesting observation between conditions as higher number of applied lower-body techniques in official than simulated matches (6 ± 3 and 3 ± 1, respectively); effort:pause ratio also differed between conditions (1:1.5 and 1:1, respectively); moreover, the authors reported greater scores of rating of perceived exertion in official compared to simulated match (14 ± 2 a.u. and 12 ± 2 a.u.).

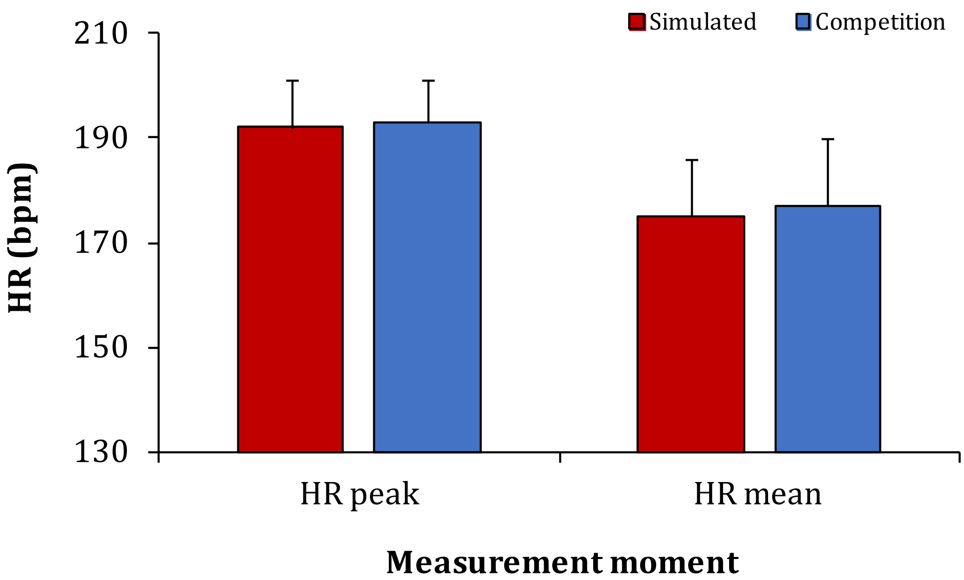


Figure 13: Peak and mean heart rate response in simulated and competitive karate matches (Adapted from Chaabéne et al. [48]).

Table 6: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in karate.

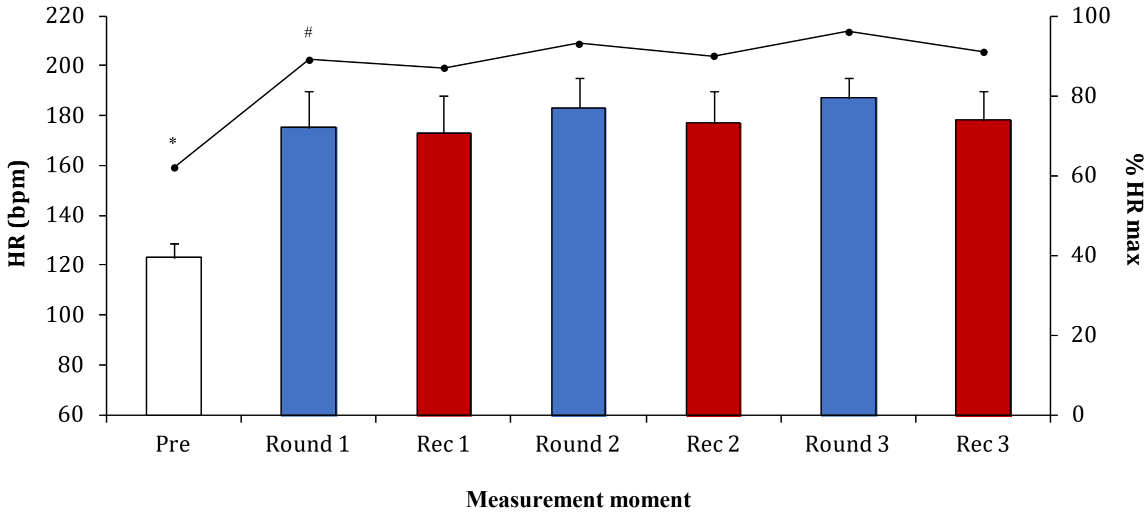
	HR	**VO_2**
Are there studies describing these variables?	Yes	Yes
Are there mean values during the match?	Yes	Yes
Are there post-match values?	Yes	NS
In a single match, is there an increase in pre-match values?	Yes	Yes
In a single match, but fragmenting the total duration of match, is there an increase in values?	NS	NS
At what point does this increase occur?	NS	NS
Is there a progressive increase in these values?	NS	NS
Mean and post-match values represent what percentage of the maximum values of these variables?	Mean 93%	Mean 48- 72%
Mean and peak values during match, represent what percentage of the anaerobic thresholds of these variables?	Below	Below
In a single match, is there a difference between the values of the simulated matches and the real matches?	No	NS
In multiple matches, simulated or official, is there a different response?	NS	NS

NS= no studies were found investigating this variable.

2.2.3. Taekwondo

Aiming to analyze the effort intensity in the taekwondo match, Chiodo et al. [49] measured HR of seven women and ten men (13 and 14 years old) in the first combat of national competition (three 2-min rounds interspersed by 1-min pause). HR values were registered in 5s interval periods and expressed in %HR of maximal values attained during the match, considering five intensity zones: (1) >95%; (2) 86-95%, (3) 76-85%; (4) 66-75%; (5) <65%. Average HR during the whole match was 187 ± 11 bpm, corresponding to 90 ± 5% of HR_{max}, and peak values ranged between 194 and 205 bpm. Efforts were performed between 86-95% and above 95% of HR_{max} higher than further classifications.

In turn, Bridge et al. [50] analyzed HR of 8 black belt England athletes, one from each weight category, in 12 matches during an international competition. Each match was composed of three 2-min rounds interspersed by 30s pause). HR acquisition was done in effort and recovery periods, and in pre-match periods (2-min), registered in 5s periods and, posteriorly, they calculated the average and standard deviation of three periods. Moreover, these values were expressed relative to the maximal values of each athlete using equation 220 – age. Finally, these values were classified in intensity zones according American College of Sports Medicine [51]: (1) 55-69; (2) 70-89%: (3) 90-99%; (4) 100%. The authors observed that absolute and relative HR values during the match in rounds 1, 2 and 3 were higher than values observed before the beginning of the match (Figure 14), as well as absolute and relative values of round 1 were lower than round 3. Moreover, they observed a difference between rounds regarding time spent on each intensity zone. In round 1, athletes remained greater time proportion in zone 2 and lesser proportion in zone 3, when compared to further rounds; even in round 1, time of athletes remained in zone 1 was lower to observed in zones 2 and 3; in round 2, the athletes remained lesser time in zone 4 compared to zone 3; in round 3, athletes remained greater time proportion in zone 3 compared to zone 2.

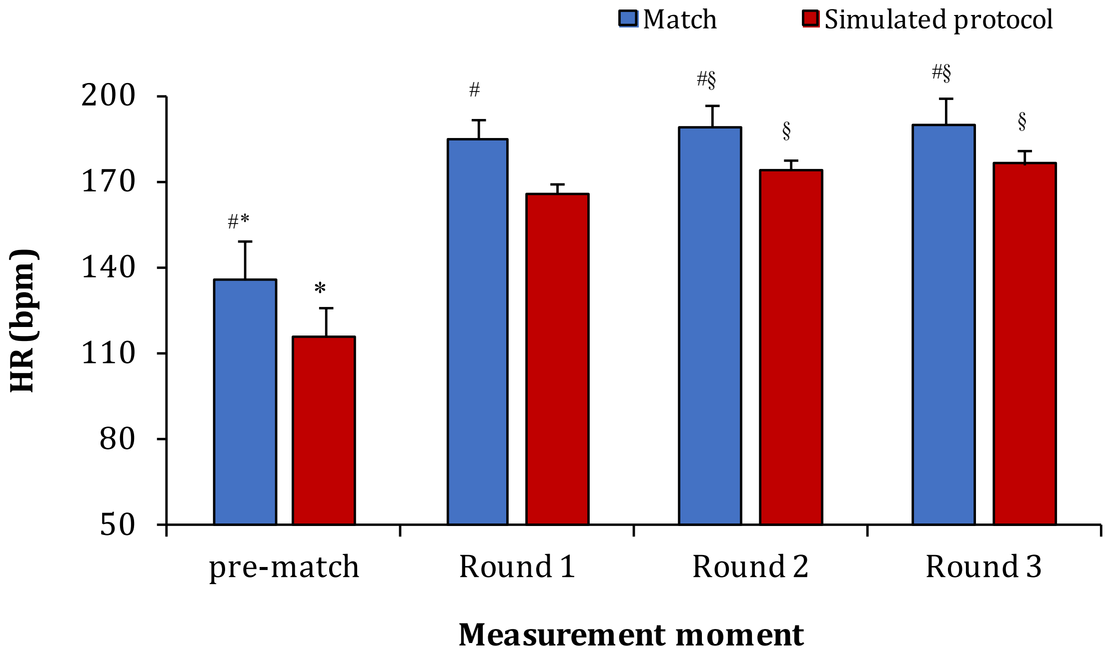


rec = recovery; * = different from rounds 1, 2 and 3 ($p < 0.05$); # = different from round 3 ($p < 0.05$).

Figure 14: Absolute (bars) and relative (continuous line; relative to maximal heart rate values calculated by equation 220 - age) heart rate response during different moments of taekwondo international competition match (three 2-min rounds 30s interval (Adapted from Bridge et al. [50]).

Bouhlel et al. [52] evaluated HR of 8 national Tunisian athletes in a simulated match composed of three 3-min rounds interspersed by 1-min recovery. Moreover, aiming to compare physiological responses in simulated match performing specific exercises, the athletes performed three protocols with different durations (10s, 1 and 3-min). The exercise chosen was a frontal kick for an athlete had to kick as fast as possible in different durations that were interspersed by 30-min recovery. At the end of the match, it was observed that HR mean values were 197 ± 2 bpm, being these values higher than rest values (54 ± 3 bpm) and correlated with maximal HR values in 10s ($r = 0.85$) and 3-min protocols ($r = 0.95$).

The comparison of physiological match demand between official match and simulates match involving taekwondo movements as conducted by Bridge et al. [53]. For that, 10 taekwondo athletes participated in an international competition and a simulated condition composed of similar actions to that performed in an official match. Time structure of both conditions was composed of three 2-min rounds interspersed by 1-min recovery. HR was measured in both conditions during rest periods, after each round and 2-min post-match. These values were expressed relative to maximal values obtained during the match. Moreover, the authors utilized an intensity zone classification and calculated time that athletes remained in each one of these zones. They verified that HR mean and peak values obtained in the match were higher than simulated protocol values (Figure 15). Proportional time remained highest HR zone (> 95% HR_{peak} of the match) was higher in the matches (65 ± 22 %) compared to the simulated protocol (4 ± 9 %). Moreover, the authors observed that HR and % HR_{peak} values increased over the match and in a simulated match.



= different from simulated protocol ($p < 0.05$); * = different from rounds 1, 2 and 3 ($p < 0.05$); § = different from round 1 ($p < 0.05$).

Figure 15: Heart rate response in different time points in an official match and in a simulated protocol, with the same time structure (three 2-min rounds interspersed by 1-min period) in taekwondo (Adapted from Bridge et al. [53]).

Campos et al. [5] estimated the contribution of the three energy systems to supply the energy cost in taekwondo simulated match using a similar method than study with karate published by Beneke et al. [4] and Doria et al. [10]. For that, 10 national and international level athletes were evaluated in a simulated match composed of three 2-min rounds interspersed by 1-min recovery between rounds. The opponents only defend themselves and they performed step actions to guarantee safety and no do not harm gas analyzer. In this condition, the authors observed that matches had an energetic cost of approximately 181 kJ. As well as observed in karate matches [14,43], it was observed a predominance of the oxidative system (66%). When energy systems contribution was presented by each round it was observed an increase over time with an absolute oxidative contribution in round 1 (98 ± 15 kJ) lower than in rounds 2 (127 ± 14 kJ) and 3 (134 ± 18 kJ). An opposed result occurred with the glycolytic contribution, which presented a reduction over the match.

In this same study [5], VO_2 and HR averages were calculated for each round. For VO_2 there was only increase in second (52.1 ± 5.9 $ml.kg^{-1}.min^{-1}$) and third rounds (53.4 ± 5.9 $ml.kg^{-1}.min^{-1}$) compared to first round (44.4 ± 6.2 $ml.kg^{-1}.min^{-1}$). In contrast, HR present a distinct outcome being that first round values (156 ± 9 bpm) were lower than values round 2 (169 ± 9 bpm) and 3 (175 ± 10 bpm); HR in round 2 was lower than during round 3. These results demonstrated that HR/ VO_2 relationship is not linear. In fact, there seems to be a difference in kinetics in heart rate and VO_2 kinetics in constant load exercises. Zucarelli et al. [54], for example, verified that component of the HR kinetics was faster than that of the VO_2 kinetics, and during exercise above gas exchange threshold the relative amplitude of the HR slow component was greater than the relative amplitude of the slow component of the O_2 kinetics. Furthermore, it is important to consider that these difference in the HR and VO_2 kinetics indicates that caution should be taken when considering mean values calculated in rounds.

Matsushigue, Hartmann, and Franchini [55] analyzed HR response of 14 taekwondo athletes during competition (Brazilian championship *Songahm* style). Moreover, HR comparison was performed between losers and winners. Post-match values (183 ± 9 bpm) were higher than pre-match (113 ± 25 bpm), and there was no HR difference pre and post-match between winners (pre-match – 119 ± 20 bpm; post-match – 181 ± 11 bpm) and losers (pre-match – 106 ± 30 bpm; post-match – 188 ± 7 bpm).

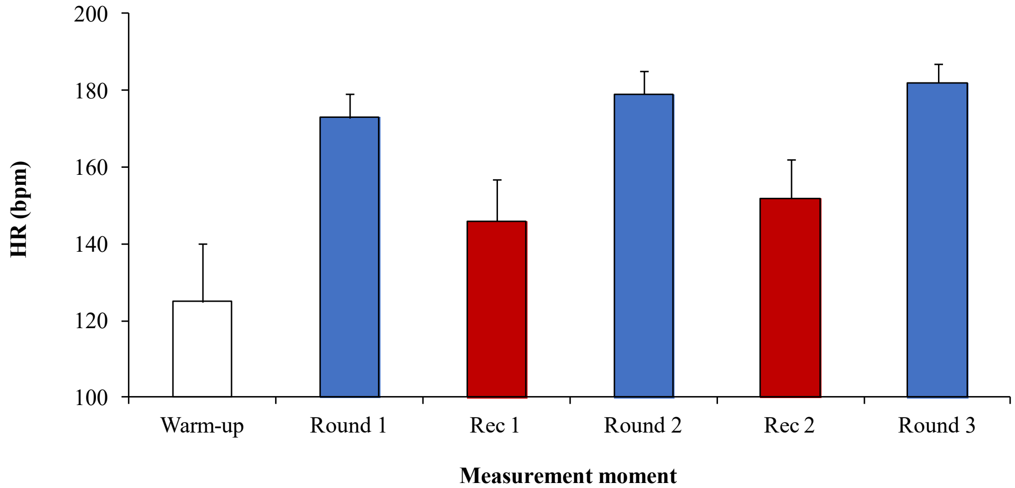
Table 7: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in taekwondo.

	HR	VO_2
Are there studies describing these variables?	Yes	Yes
Are there mean values during the match?	Yes	Yes
Are there post-match values?	Yes	NS
In a single match, is there an increase in pre-match values?	Yes	Yes
In a single match, but fragmenting the total duration of match, is there an increase in values?	Yes	Yes
At what point does this increase occur?	1° round	1° round
Is there a progressive increase in these values?	Yes	Yes, until 2nd round
Mean and post-match values represent what percentage of the maximum values of these variables?	Mean 90%	NS
Mean and peak values during match, represent what percentage of the anaerobic thresholds of these variables?	NA	NS
In a single match, is there a difference between the values of the simulated matches and the real matches?	NS	NS
In multiple matches, simulated or official, is there a different response?	No	NS

NS = no studies were found investigating this variable.

2.2.4. Boxing

Ghosh et al. [7] submitted 26 amateur boxing athletes to a simulated match during a camp training. The matches were composed by three 3-min rounds interspersed by 1-min pause, with HR measured in the warm-up, and effort and pause periods during the match. In addition, the authors compared the HR response in athletes subdivided in three weight categories: 48-57 kg (n = 7), 60-67 kg (n = 10) and 70-90 kg (n = 9). Considering all data, it was not observed difference in the HR values between the different times of measurement (Figure 16).



rec= recovery periods.

Figure 16: Heart rate response in different times of measurements during a boxing match composed by three 3-min rounds interspersed by 1-min recovery (Adapted from Ghosh et al. [7]).

Nevertheless, considering only the lightest category (48-57 kg), Ghosh et al. [7] verified higher HR values in round 3 compared to rounds 1 and 2 (Table 8). Davis et al. [56] analyzed HR and VO_2 responses exercise involving sequences of punches and movements of defense in three rounds of 2-min interspersed by 1-min pause. The sample was composed of 10 boxers (initial level). Total energy expenditure was estimated to investigate the relative contribution of the three energy systems, as well as the HR and VO_2 values. HR values of round 1 were lower than round 3 values, and HR recovery values of round 1 were lower than recovery values of round 2 (Figure 17). VO_2 values increased over time, with round 1 values lower than rounds 2 and 3 values (Figure 18). HR and VO_2 responses decreased in recovery intervals between rounds, however post-second round values were higher than first-round values (Figures 17 and 18, respectively) [56]. The match has an energetic cost about 608.6 ± 81.8 kJ, equivalent to 84 ± 8% of VO_{2max}. Relative oxidative system contribution was lesser in the first round when compared to rounds 2 and 3, being responsible by approximately 87% of the total energetic cost of the match (526.0 ± 57.1 kJ) (Figure 19) [56].

Table 8: Heart rate response in different times of measurement during a boxing match composed by three 3-min rounds interspersed by 1-min recovery in three weight categories (Adapted from Ghosh et al. [7]).

	48-57kg	60-67kg	70-90kg
Warm-up	130 ± 12	120 ± 13	123 ± 16
Round 1	175 ± 7	172 ± 6	172 ± 5
Recovery 1	146 ± 8	146 ± 13	145 ± 11
Round 2	179 ± 6	176 ± 7	180 ± 5
Recovery 2	157 ± 8	148 ± 12	151 ± 9
Round 3	186 ± 5*	183 ± 5	179 ± 4
Match	180 ± 6	177 ± 6	177 ± 5

* = different from values from rounds 1 and 3.

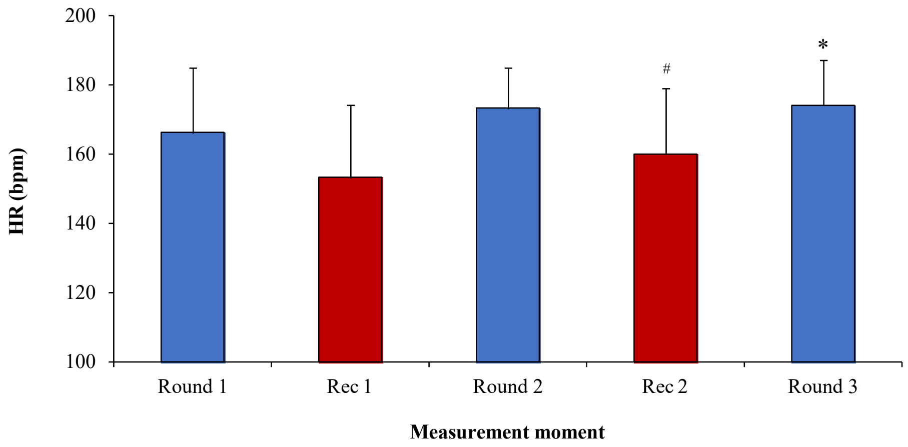


Figure 17: Heart rate response in different times of measurement in a boxing match composed by three 2-min rounds interspersed by 1-min recovery (Adapted from Davis et al. [56]).

rec. = recovery periods; * = different from round 1 ($p < 0.05$); $^{\#}$ = different from recovery period 1 ($p < 0.05$).

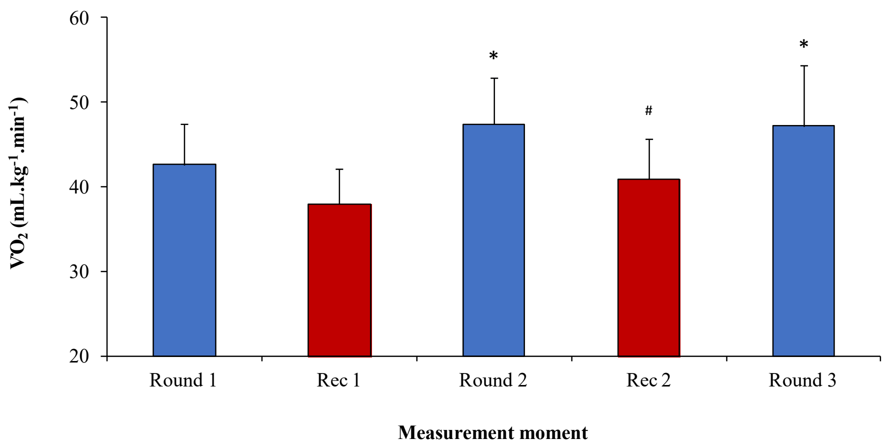


Figure 18: Oxygen consumption response in different times of measurements in a boxing match composed by three 2-min rounds interspersed by 1-min recovery (Adapted from Davis et al. [56]).

rec.= recovery periods; * = different from round 1 ($p < 0.05$); $^{\#}$ = different from recovery periods 1 ($p < 0.05$).

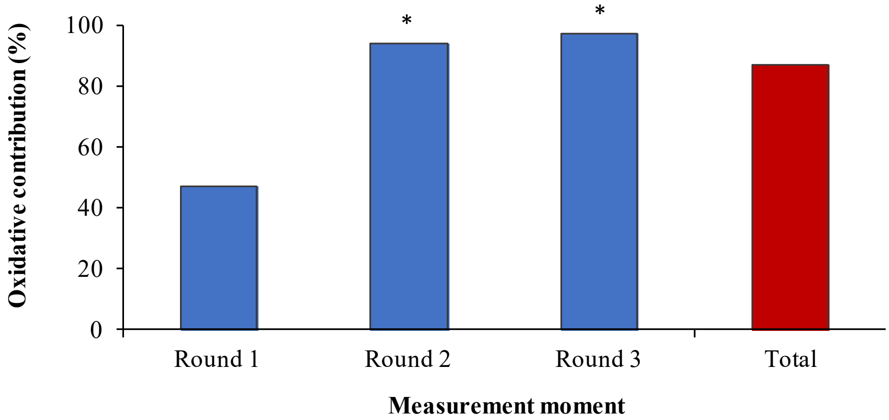


Figure 19: Relative oxidative system contribution in different times of measurements in a boxing match composed by three 2-min rounds interspersed by 1-min recovery (Adapted from Davis et al. [56]).

* = different from round 1 ($p < 0.05$).

De Lira et al. [57] evaluated HR response (maximal and equivalent to first and second ventilatory threshold) in a simulated match (three 2-min rounds interspersed by 1-min between rounds) during the match and in recovery intervals in 10 boxers (six men and four women). Maximal indexes (HR_{max}: 193 ± 7 bpm; and VO_{2max}: 52.2 ± 7.2 $ml.kg^{-1}.min^{-1}$) and submaximal associated to ventilatory threshold 1 (HR: 167 ± 9 bpm; VO_2: 40.5 ± 5.9 $ml.kg^{-1}.min^{-1}$) and 2 (HR: 181 ± 6 bpm; VO_2: 47.7 ± 6.0 $ml.kg^{-1}.min^{-1}$) were identified in maximal incremental test. HR and % HR_{max} remained higher in rounds 2 (HR: 183 ± 6 bpm; $\%HR_{max}$: 95 ± 3%) and 3 (HR: 186 ± 7 bpm; $\%HR_{max}$: 96 ± 2%) when compared to round 1 (HR: 175 ± 11 bpm; $\%HR_{max}$: 91 ± 5%). HR recovery (delta %) did not differ between rounds (round 1: -18 ± 13%; round 2: -13 ± 6%; round 3: -16 ± 7%). Moreover, an important information reported in this study was the calculation of the time spent in intensities below or above ventilatory threshold 1 and 2 using HR. The authors showed a decreasing in time below ventilatory threshold 1 and increasing time above ventilatory threshold 2 over time (round), as shown in table below. Approximately, 60% of the match, the HR remained above ventilatory threshold 2 showing high solicitation of oxidative metabolism (Table 9).

Table 9: Percentage of time spent in intensities below and above ventilatory thresholds in a boxing match simulation (three 2-min rounds interspersed by 1-min interval between rounds) (Adapted from De Lira et al. [57]).

		Below VT1 (%)	Between VT 1 and 2 (%)	Above VT 2 (%)
Round 1	HR	19 ± 20*	40 ± 30*	41 ± 36*
	VO_2	16 ± 14	52 ± 29	32 ± 34
Round 2	HR	7 ± 6	18 ± 6	75 ± 11
	VO_2	7 ± 6	22 ± 10	70 ± 14
Round 3	HR	6 ± 13	12 ± 5	83 ± 12
	VO_2	4 ± 6	18 ±10	79 ± 14

VT = ventilatory threshold; * = different from rounds 2 and 3 ($p < 0.05$).

Table 10: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in boxing.

	HR	VO_2
Are there studies describing these variables?	Yes	Yes
Are there mean values during the match?	Yes	Yes
Are there post-match values?	No	NA
In a single match, is there an increase in pre-match values?	Yes	Yes
In a single match, but fragmenting the total duration of match, is there an increase in values?	Yes	Yes
At what point does this increase occur?	1st round	1st round
Is there a progressive increase in these values?	Yes	Yes, until 2nd round
Mean and post-match values represent what percentage of the maximum values of these variables?	Mean 91-96%	Mean 84%
Mean and peak values during match, represent what percentage of the anaerobic thresholds of these variables?	Above	Above
In a single match, is there a difference between the values of the simulated matches and the real matches?	NA	NA
In multiple matches, simulated or official, is there a different response?	NA	NA

NS = no studies were found investigating this variable.

3. Cardiovascular responses and oxidative solicitation in specific activities

In the present topic will be presented studies that measured cardiovascular responses in specific exercises. Variables presented will be the same described in above topic: VO_2, HR, and oxidative contribution in these specific exercises. This sequence will be organized to present grappling and striking combat sports.

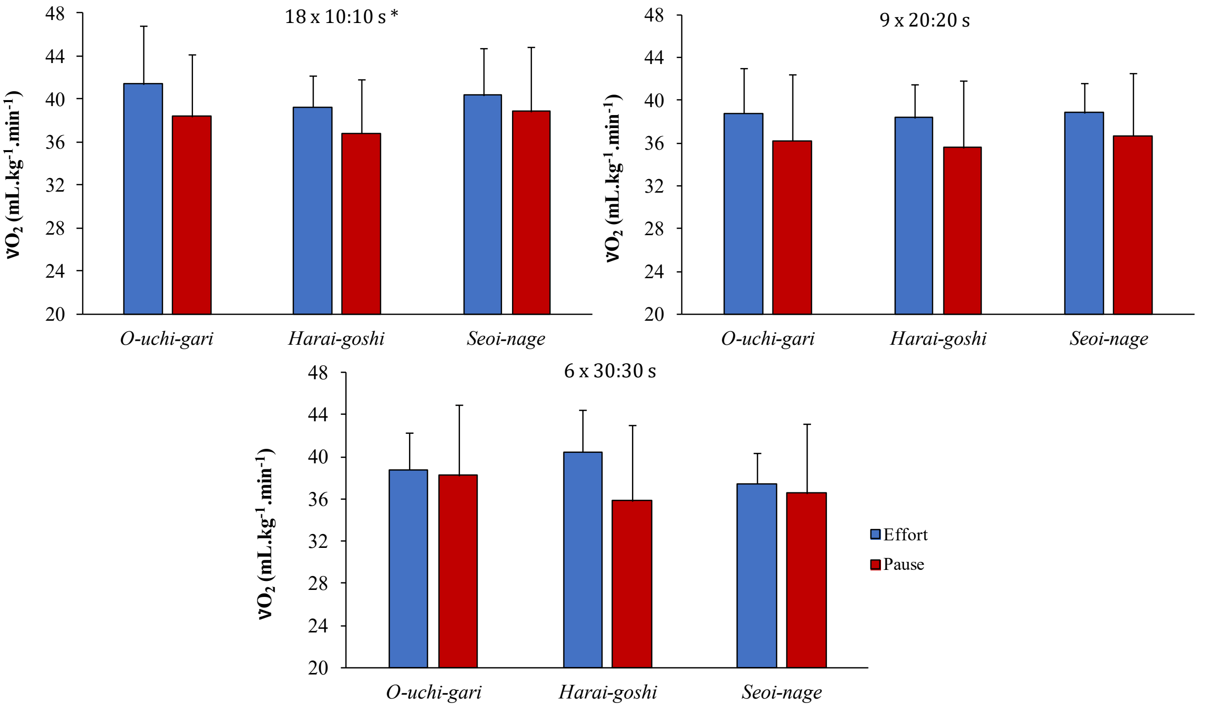
3.1. Grappling combat sports

3.1.1. Judo

Franchini et al. [58] measured the HR, energetic cost and estimate three energy systems contribution to supply the energy cost in three judo throwing techniques (*morote seoi-nage* - arm technique, *harai-goshi* - hip technique, and *o-uchi-gari* - leg technique) during *nage-komi* in 12 judo athletes. For thus, were performed three experimental sessions each one for execution of each technique with de 5-min duration, with athlete throwing opponent each 15s. VO_2 was higher during *morote seoi-nage* technique (33.7 ± 5.7 ml.kg^{-1}.min^{-1}) and *harai-goshi* (32.3 ± 5.1 ml.kg^{-1}.min^{-1}) compared to *o-uchi-gari* (30.0 ± 6.1 ml.kg^{-1}.min^{-1}). Oxidative relative contribution (%) was not different between techniques (84.0 ± 3.8% *o-uchi-gari*; 82.3 ± 3.8% *harai-goshi*; 82.2 ± 2.9% *morote seoi-nage*), while oxidative absolute contribution was different, with higher values in *morote seoi-nage* (223 ± 66 kJ) compared to *o-uchi-gari* (196 ± 74 kJ) and *harai-goshi* technique (211 ± 66 kJ). Total energetic cost was higher in *morote seoi-nage* (273 ± 86 kJ) compared to *o-uchi-gari* (237 ± 99 kJ) and *harai-goshi* techniques (259 ± 91 kJ). HR did not differ between techniques showing that it is not an accurate measurement to quantify energy expenditure or intensity in this type of exercise.

Baudry and Roux [59] submitted 10 adolescent judo athletes (2 girls and 8 boys) to a circuit with specific activities of judo varying effort and pause ratio in three sessions separated by one week (6 x 40s with three different intervals of 40, 120 and 200s and effort:pause ratio of 1:1; 1:3; 1:5). Each set was composed by one or two different exercises: a) *hikidashi* (involves pulling the partner to prepare for shoulder throws); b) *hikidashi* + *uchi-komi* (a drill in which one performs the throwing movement but excludes the throwing phase); c) *uchi-komi*; d) *hikidashi* + *nage-komi* (a drill in which one performs the whole throwing movement); e) *nage-komi*; f) *uchi-komi* + *nage-komi*. All exercises were performed in the maximal intensity (all-out) and HR was measured in the rest, during and post-30-min of the end of the exercise. To compared values from effort and pause periods it was calculated 5s average period; resting and post warm-up values, as well as at 5 and 30-min periods after circuit it was calculated 30s average. The authors [59] observed that to three sessions, HR at the end of the last set was different from rest values, without differences between sessions. Considering sessions values, they did not observe difference between sessions 1:1 and 1:3. Above all, HR values in session 1:5 were lower in 2nd, 4th and 6th set compared with same times of session 1:1; and in 2nd and 4th sets compared to the same time of session 1:3. HR values in the end of pause periods were higher in 1:1 compared to 1:3 and 1:5, except in 5th set, that was not different between 1:1 and 1:3. Considering the difference between HR at the end of pause periods and at the end of the next effort period, range for each effort period was lower in session 1:1 compared to 1:3 and 1:5; lower in session 1:3 compared to 1:5. This result was more evident in effort period when difference was about 16 ± 11 bpm in 1:1; 41 ± 13 bpm in 1:3 and 63 ± 9 bpm in 1:5.

Aiming to compare HR and VO_2 of different *uchi-komi* protocols performed with different techniques and time structure, Franchini, Panissa and Julio [11] submitted 10 judo athletes to 9 *uchi-komi* experimental sessions performed in the highest intensity (all-out). Three techniques were analyzed, being arm (*morote-seoi-nage*), leg (*o-uchi-gari*) and hip techniques (*harai-goshi*) in three different intermittent time structure. It was used the same duration to effort and pause periods, however, there was variation in the effort periods with the same 3-min session total duration: 18 x 10s, 9 x 20s or 6 x 30s. The authors also calculated the energetic cost of each one of the nine experimental sessions. As all efforts were performed all-out, it was not observed any difference in absolute energetic cost between different techniques and time structure. However, the athletes performed greater number of leg techniques compared to the other two techniques, with energetic cost to perform these techniques inferior than the energetic cost of arm techniques. VO_2 during effort in the 18 x 10:10s temporal structure was higher than VO_2 during effort of 6 x 30:30s (Figure 20). VO_2 values were lower in the first minute of effort compared to the second and third minutes, as well as second minute values of effort were lower than third minute values (Figure 21). HR values during effort and pause were lower than in the first minute of exercise if compared to the second and third minutes; the second minute values of exercise were lower than the third minute values (Figure 22).



* = higher values in 18 x 10:10s compared to 6 x 30:30s during effort periods ($p < 0.05$).

Figure 20: Oxygen consumption values during efforts (blue bar) and pause periods (red bar) in all-out *uchi-komi* sessions using different techniques and time structures (Adapted from Franchini, Panissa and Julio [11]).

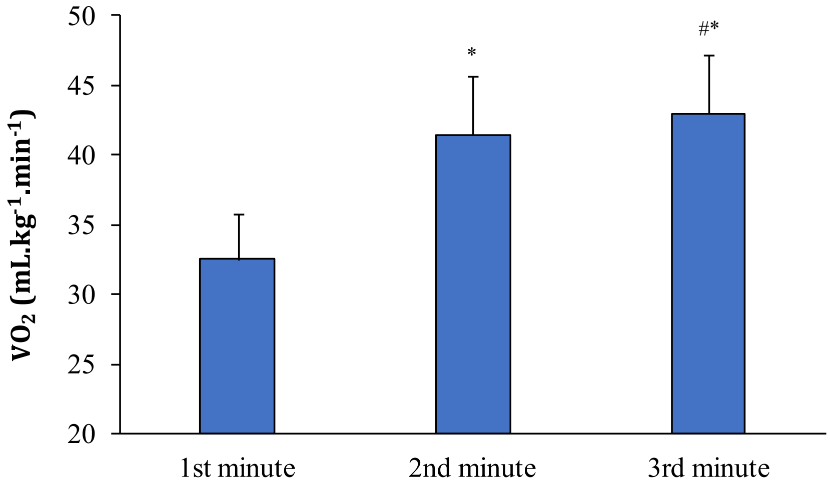


Figure 21: Oxygen consumption values during a 3-min effort during all-out *uchi-komi* sessions using different techniques and time structures (Adapted from Franchini, Panissa and Julio [11]).

* = higher values than the first minute of effort ($p < 0.05$); # = higher values than the second minute of effort ($p < 0.05$).

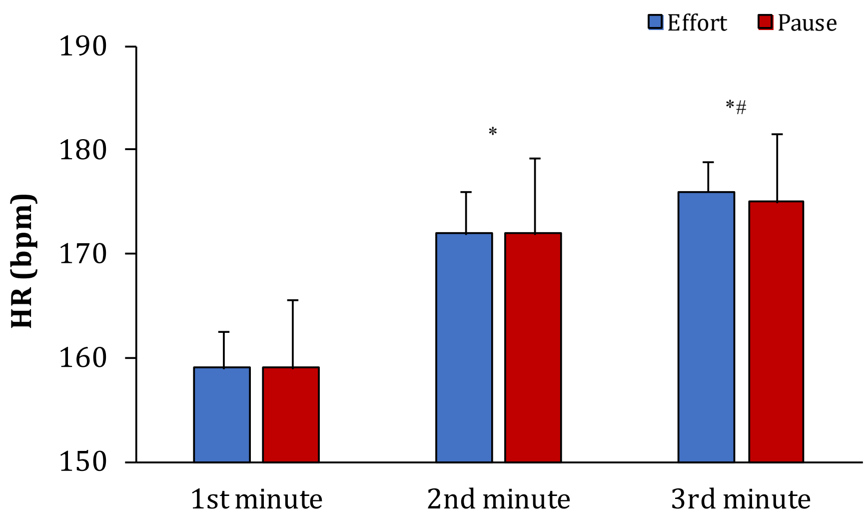


Figure 22: Heart rate values during a 3-min effort and pause during all-out *uchi-komi* sessions using different techniques and time structures (Adapted from Franchini, Panissa and Julio [11]).

* = higher values than the first minute of effort and pause ($p < 0.05$); # = higher values than the second minute of effort and pause ($p < 0.05$).

3.2. Striking combat sports

3.2.1. Karate

Imamura et al. [60] analyzed HR, %HR_{max} (determined in treadmill maximal incremental test) and %HR reserve response during execution of 1000 punches and 1000 kicks with alternated segments, and 5-min interval between two types of exercise in highly skilled black belt (n = 6) and novice white belt athletes (n = 8) (~15-min session duration). HR was registered each minute until the fifth minute and after that, it was registered each 3-min. HR values are presented in Table 11.

Table 11: Heart rate response in rest and during two types of exercise (1000 punches and 1000 kicks interspersed by 5-min recovery) (Adapted from Imamura et al. [60]).

		Rest	**1000 punches**	**1000 kicks**	**Recovery**
HR (bpm)	Experienced	69 ± 5	103 ± 15$^{\#}$	127 ± 12$^{\#\S}$	83 ± 13§*
	Novice	71 ± 10	116 ± 18$^{\#}$	137 ± 14$^{\#\S}$	87 ± 7$^{\#\S*}$
HR (% HR_{max})	Experienced	-	53 ± 9	66 ± 8§	43 ± 7§
	Novice	-	58 ± 8	70 ± 7§	44 ± 3§
HR (% HR_{res})	Experienced	-	27 ± 13	47 ± 13§	-
	Novice	-	35 ± 13	52 ± 13§	-

HR = heart rate; % HR_{max} = percent of maximal heart rate obtained in maximal incremental test; % HR_{res} = percent of heart rate reserve; $^{\#}$ = different from rest ($p < 0.05$); § = different from 1000 punches ($p < 0.05$); * = different from 1000 kicks ($p < 0.05$).

For experienced group, HR values in both exercises were higher than rest values. There was a difference between exercises, with 1000 punches values lower than 1000 kicks. Regarding %HR_{max}, 1000 punches values were lower than 1000 kicks and higher than recovery values. Regarding % HR_{res}, 1000 punches values were lower than 1000 kicks. For novice group, HR values measured in both exercises were higher than rest and recovery periods; there were a difference between exercises with lower values in 1000 punches compared than 1000 kicks. Regarding % HR_{max} and % HR_{res} results obtained were the same of experienced group. In both sessions HR remained intensity considered moderate [60].

The same group of researchers [61], repeated the aforementioned protocol with 1000 punches and 1000 kicks, however they added VO_2 measurement during the session. In the punch session, VO_2 average was 7.4 ± 0.7 ml.kg^{-1}.min^{-1}; equivalent to 17 ± 4% of VO_{2max}. HR values were 108 ± 13 bpm, which was equivalent to 57 ± 6% of HR_{max}. In the kick session, VO_2 average was 17.3 ± 3.7 ml.kg^{-1}.min^{-1}, equivalent to 41 ± 9% of $VO_{2máx}$. HR values were 156 ± 12 bpm, equivalent to 83 ± 6% HR_{max}. Considering the two aforementioned described studies [60,61] it can be concluded that the exercises analyzed presented low values for the HR and VO_2 responses.

Imamura et al. [62] and Imamura et al. [63] analyzed HR and VO_2 responses during four types of karate training: 1) S-basics (punching, kicking, blocking and striking in stationary position); 2) M-basics (punching, kicking, blocking and striking with body movements in various formal stances); 3) TECH1 (sparing techniques without an opponent); 4) TECH2 (sparring techniques against an opponent). The sessions had 15-min duration for S- basics and TECH2 and 10-min para M- basics and TECH1. The exercises were performed sequentially with 5-min interval between each exercise. VO_2 was measured by Douglas bag during exercise in 1, 5 and 10-min to M-basics and TECH1 and 5, 10 and 15-min for S- basics and TECH2, and in intervals between exercises (5-min immediately after completing training session). HR was registered in the same moments. Moreover, the athletes also performed a maximal incremental test to obtain HR_{max} and VO_{2max}.

These two studies [62,63] were conducted aiming to observe HR and VO_2 in these types of karate exercises and to verify if the intensity maintained would be enough to improve VO_{2max} based in recommendations of American College of Sports Medicine (ACSM) [51], which preconize that to maintain or improve aerobic fitness, the minimum intensity is 53-64% of HR_{max}, 50% VO_{2max} or 40-50% VO_{2res}.

In the study published in 1999 [62], only men were included. They attained VO_{2max}, and HR_{max} in treadmill maximal incremental test of 58.6 ± 6.8 ml.kg^{-1}.min^{-1} and 198 ± 8 bpm, respectively. Mean %VO_{2max} and % HR_{max} for S-basics were below the threshold preconized by the ACSM [51], while M-basics, TECH1, and TECH2 were above this threshold. HR and VO_2 values in the study of Imamura et al. [62] are presented in Table 12.

Table 12: Heart rate response and oxygen consumption during four types of karate training (Adapted from Imamura et al. [62]).

	HR (bpm)	$\%HR_{max}$	VO_2 (ml.kg^{-1}.min^{-1})	$\%VO_{2máx}$
S-basics	123 ± 25	39 ± 16	13.9 ± 4.1	22 ± 7
M-basics	176 ± 24	66 ± 13	30.1 ± 5.0	53 ± 9
TECH1	180 ± 26	84 ± 17	30.4 ± 3.9	55 ± 7
TECH2	174 ± 23	79 ± 13	30.9 ± 5.5	55 ± 10

HR = heart rate; % HRmax = percent of maximal heart rate; VO2 = oxygen consumption; %VO2max = percent of maximal oxygen consumption; S-basics = composed of punching, kicking, blocking and striking in stationary position; M-basics = composed of punching, kicking, blocking and striking with body movements in various formal stances; TECH1 = composed of sparing techniques without an opponent; TECH2 = composed of sparring techniques against an opponent.

In turn, Imamura et al. [63] analyzed only women. They attained HR_{max} 193 ± 7 bpm and VO_{2max} 40.9 ± 5.4 ml.kg^{-1}.min^{-1}. The authors utilized the percentual of HR_{res} and VO_{2res} as intensity parameters. VO_2, $\%VO_{2res}$, % HR_{max} and % HR_{res} average in S-basics were below the preconized threshold by the ASCM and M-basics above the threshold. For TECH1 and TECH2, % HR_{max} and HR_{res} average were above the threshold, although the % VO_{2res} had been below this threshold. Moreover, the authors observed that women maintained lower intensity than men to perform the four types of karate training. HR and VO_2 values from Imamura et al. [63] study are presented in Table 13.

Table 13: Heart rate and oxygen consumption response in four types of training (Adapted from Imamura et al. [63]).

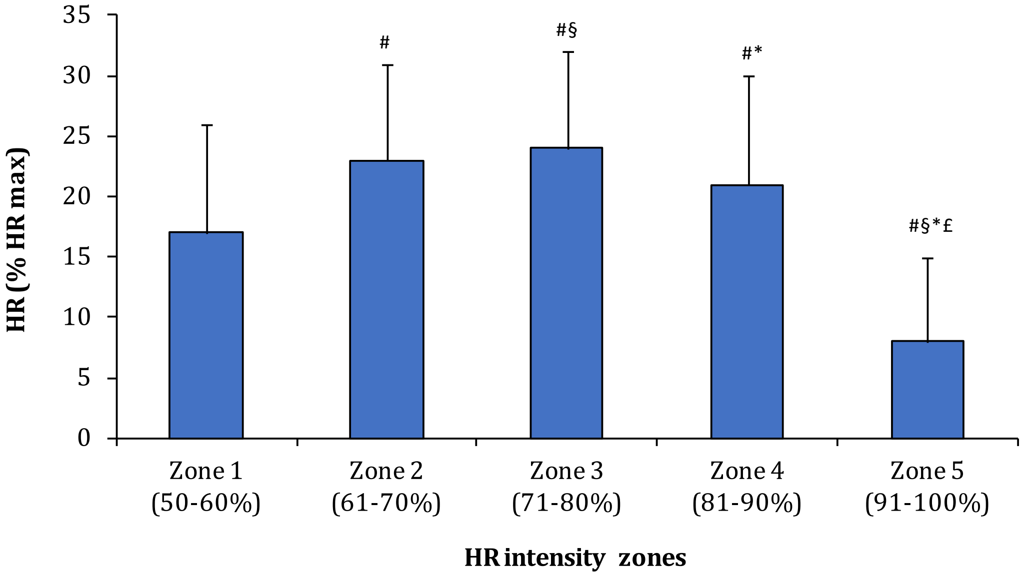
	HR (bpm)	HR ($\%HR_{max}$)	HR ($\%HR_{res}$)	VO_2 (ml·kg^{-1}·min^{-1})	VO_2 ($\%VO_{2res}$)
S-basics	100 ± 10	23 ± 5	35 ± 5	9.4 ± 0.9	20 ± 2
M-basics	145 ± 15	43 ± 8	65 ± 8	20.8 ± 2.8	47 ± 5
TECH1	145 ± 20	43 ± 8	63 ± 10	17.0± 1.9	38 ± 5
TECH2	140 ± 10	40 ±5	63 ± 5	15.0 ± 0.9	32 ± 2

HR = heart rate; $\%HR_{máx}$ = percent of maximal heart rate; VO_2 = oxygen consumption; % $VO_{2máx}$ = percent of maximal oxygen consumption; % HR_{res} = percent of heart rate reserve; % VO_{2res} = percent reserve of oxygen consumption reserve; S-basics = composed of punching, kicking, blocking and striking in stationary position; M-basics = composed of punching, kicking, blocking and striking with body movements in various formal stances; TECH1 = composed of sparing techniques without an opponent; TECH2 = composed of sparring techniques against an opponent.

Posteriorly, Milanez et al. [64] also evaluated the HR response during a karate training session (n = 9). After the determination of the variables related to the treadmill maximal incremental test (VO_2, %HR, %HR ventilatory threshold and respiratory compensation point - RCP), the athletes were submitted to a typical karate training session (shorter effort periods with duration of 2-min; basic techniques, combined techniques and combined techniques against opponent; small intervals of 30s and 60s were used to change techniques or resting). HR was analyzed during whole session and divided in intensity zones, establishing the time (minutes) that athletes remained in each intensity zone (Zone 1: 50 to 59% of HR_{max}; Zone 2: 60 to 69% of HR_{max}; Zone 3: 70 to 79% of HR_{max}; Zone 4: 80 to 89% of HR_{max}; Zone 5: 90 to 100% of HR_{max}). Session duration was 91-min and it was observed a difference between time that athletes remained in each intensity zone, with time in zones 1 (0.42-min) and 5 (6.17-min) lower than time in zones 2 (22.08-min), 3 (23.33-min) and 4 (22.17-min). HR at the ventilatory threshold and at the RCP were equivalent and represented, respectively, 83% and 90% of HR_{max}. Although most of the time had occurred between 60% and 90% of $HR_{máx}$, the karate athletes remained predominantly below the intensity correspondent to the ventilatory threshold. However, it is important to note that the thresholds in this study [64] were observed in high percentages of HR_{max} (83-90%) %), and caution should be taken when considering that karate athletes train mostly below the ventilatory threshold.

3.2.2. Taekwondo

Haddad et al. [65] measured the HR (registering each 5s) of 12 young athletes (15 ± 2 years-old) during training sessions (involving plyometrics, sprints/velocity and technical-tactical of taekwondo training) in the pre-season (12 weeks, four times per week, ~90-min per session). The authors divided the HR response in five intensity zones (50-60%; 61-70%; 71-80%; 81-90%; 91-100%) and reported time (%) in each one of these zones (Figure 23). Maximal HR utilized was obtained using the Yo-Yo intermittent test [66]. Each athlete performed a minimum of 20 sessions. Additionally, they utilized the rating of perceived exertion ($RPE_{session}$), TRIMP (training impulse) from Banister [67] and from Edwards [68] to quantify the internal load aiming to investigate the exercise intensity distribution (time in each HR zone) and RPE duration in the session. There were differences between all intensity zones, except between zones 2 and 4 (Figure 22) being that 24.9% of variation of $RPE_{session}$ was explained by time in zone 5 (21.9%) and by session duration (3.2%). In this way, $RPE_{session}$ is minimal influenced by session duration and by time remained in the highest intensity.



= different from zone 1 ($p < 0.05$); § = different from zone 2 ($p < 0.05$); * = different from zone 3 ($p < 0.05$); £ = different from zone 4 ($p < 0.05$).

Figure 23: Percent of maximal heart rate response in all pre-season training sessions (Adapted from Haddad et al. [65]).

Bouhel et al. [52] analyzed the HR responses during training protocols and simulated match aiming to verify the association of the HR during the match with data from training protocols. In addition, they conducted a shuttle-test proposed by Léger and Lambert [69] to asses HR and VO_{2max}. For this, 8 Tunisian national team athletes participated in the study. Exercise session was composed by three exercises 10s, 1 and 3-min durations using maximal number of frontal kicks performed in a racket held by a trainer in abdomen height. Each exercise was interspersed by 30-min and these durations were used aiming to access the three energy transfers systems in the different exercises (ATP-PCr, glycolytic and oxidative). The simulated match was composed of three 3-min rounds with 1-min recovery. HR increased during competition compared to rest, and HR_{max} at the final of the match (197 ± 2 bpm) was correlated with HR_{max} in 10s and 3-min exercise.

Pieter et al. [70] compared the HR in seven men with 31 months of taekwondo experience in four forms of exercises frequently used by beginners 1) *kich'o il bu* – 15 sets (average of 24s of effort) with 45s of active recovery; 2) *t'aeguk i jang* - 15 sets (average of 20s effort) with 45s of active recovery; 3) Combo 1: combination of various types of kicks (30s effort) with 60s of recovery; 4) Combo 2: combination of various types of kicks and punches (30s effort) with 60s of recovery. HR was measured during the last 10s of each effort and recovery interval and also during the recovery intervals. There was a difference between exercise and recovery, however there was no difference between the two exercise forms *kich'o il bu* (160 bpm) and *t'aeguk i jang* (159 bpm) neither between combo 1 (182 bpm) and combo 2 (181 bpm). However, both combos presented higher values than the other two exercise forms.

Toskovic et al. [71] analyzed the HR and VO_2 responses of 28 taekwondo athletes during a 20-min exercises session, composed of punches, kicks, jump with kick and step. These responses were compared between sexes (men and women) and training level (beginners and experienced). Considering only men experienced athletes (n = 7), HR values during the session (170 ± 15 bpm), expressed relative to HR_{max} obtained in treadmill maximal incremental test, reached 90 ± 6%. Absolute VO_2 values during the session (~41.84 ± 5.83 $ml.kg^{-1}.min^{-1}$), expressed as the percentage of values obtained in the maximal incremental test reached values 72 ± 7%. Energetic cost of this session was 286.5 ± 35.6 kcal.

Haddad et al. [72] submitted 18 adolescent athletes to two training sessions composed of four 4-min blocks interspersed by active recovery, with one session with specific movements of this modality and another with non-specific movements. In each effort block, the athletes exercise 10s (kicks or running in the intensity equivalent to 90-95% of maximal HR) and had 20s passive recovery. The authors did not observe difference in HR values expressed as percentage of HR_{res} between the two types of training (73 ± 5% in running; and 71 ± 5% in specific movements). Additionally, the authors did not observe difference in the internal load calculated by the method proposed by Banister (75 ± 10 a.u. in running; 72 ± 11 a.u. in specific training) and by the method proposed by Edwards (117 ± 13 a.u. in running; 114 ± 13 a.u. in specific training). These data show the possibility to prescribe aerobic training using specific movements of this modality from percentage of HR_{res}.

During six sessions performed in five training camp days, Bridge et al [12] analyzed HR of 8 experienced athletes. HR recording was done each 5s and the activity performed were registered in a diary and separated in 8 categories (Table 14), being calculated the mean values for each activity. The authors verified that after six sessions, the athletes had trained during 360-min, excluding warm-up periods, low-intensity running and pause. Average HR was 148 ± 13 bpm and the intensity of activities range between moderate and heavy. Mean HR responses were similar in elastics, technical combinations, and step sparring. However, these responses were lower than HR responses obtained in remaining activities. The practice of pad work resulted in higher mean HR response than practice of elastics, technical combinations, and step sparring practices, but lower HR response than practice of forms, basic technique and forms, sparring drills, and free sparring. Moreover, HR response in forms, basic technique and forms, sparring drills, and free sparring were similar, but higher than remaining activities practice.

Table 14: Heart rate response in different taekwondo exercises measured in six sessions during five training camp days (Adapted from Bridge et al. [12]).

	Total time (min) and (% from total)	HR (bpm)	HR (% of HR_{max})	Intensity
Elastics	105 (19)	128 ± 13	65 ± 6	Moderate
Step sparring	40 (7)	133 ± 16	67 ± 10	Moderate
Technical combinations	27 (5)	137 ± 18	69 ± 8	Moderate
Pad work	91 (16)	148 ± 15	75 ± 8	Heavy
Forms	20 (4)	157 ± 19	80 ± 9	Heavy
Basic techniques and forms	26 (5)	158 ± 24	80 ± 11	Heavy
Sparring drills	30 (5)	160 ± 17	81 ± 9	Heavy
Free sparring	21 (4)	161 ± 15	81 ± 7	Heavy
Entire training camp activities	360 (64)	148 ± 13	75 ± 7	Heavy

3.2.3. Boxing

Arsenau, Mekary and Léger [73] quantified the physiological response of 9 boxers who performed standardized exercises at a gymnasium and in the laboratory. In that situation, considering the impossibility to measure VO_2 during a match competition, the authors developed and validated a method to estimate these values using VO_2 post-exercise. Exercises were performed as 2-min rounds followed by 1-min recovery interval. In the protocol performed at the gymnasium, the athletes performed three sequences of typical exercises interspersed by 10-min recovery interval: (a) shadow boxing (two rounds); (b) sparring (three rounds); (c) freely hitting a punching bag weighing 34 kg (three rounds). In the laboratory session four sequences of typical exercises were performed: (a) shadow boxing (two rounds); (b) sparring (three rounds); (c) combination of four different movements in the pad work (three rounds); (d) freely hitting a punching bag weighing 25 kg (three rounds), increasing frequencies of the rounds (60, 120 and 180 beats per minute for rounds 1, 2 and 3, respectively). During all exercises, HR was continuously measured and data registered each 5-s period, except in the first exercise, *i.e.*, shadow boxing. In addition, in the laboratory session VO_2 was measured only at the end of the third round in the sparring and pad work and continuously in the rounds freely hitting a punching bag. Validation of this method (VO_2 measurement only at the end of the exercise) as physiological demand from whole activity was described in an article in which the explanation involves an experiment with nine college students that ran in three different intensities and VO_2 was measured during and after that. The authors conducted this validation to respond some questions about the utilization of this method in boxing. It is important to highlight that this method is feasible only for continuous exercise that allow a steady state at least during 2-min being that an alternative to measure VO_2 in sessions with continuous cadence. However, during a match, which is intermittent, the utilization of this method and the results obtained must be seen with caution.

Considering that sparring was the unique activity performed in the same form in two sessions, Arsenau, Mekary and Léger [73] observed that the mean values of $\%HR_{max}$ (obtained in the treadmill maximal incremental test) in the three rounds in the gymnasium (92 ± 4%) were higher than the values obtained in the laboratory (86 ± 6%), even if punches frequency had been similar (36 ± 10 and 35 ± 7 punches per minute, respectively). For the session performed in the gymnasium, the authors also observed an increase in percentage of HR_{max} over the rounds, in the sparring and in the activity freely hitting a punching bag (Figure 24), and increase of punches frequency in freely hitting a punching bag activity. In addition, percentage of HR_{max}, the values observed in the sparring were higher than the values observed in activities freely hitting a punching bag, whereas an opposite behavior was observed for punches frequency. In the session performed in the laboratory, the authors [73] observed an increase in the percentage of HR_{max} only from round 1 to round 2, in the sparring and in the pad work (Figure 25), while punches frequency increased in the same moments only for pad work.

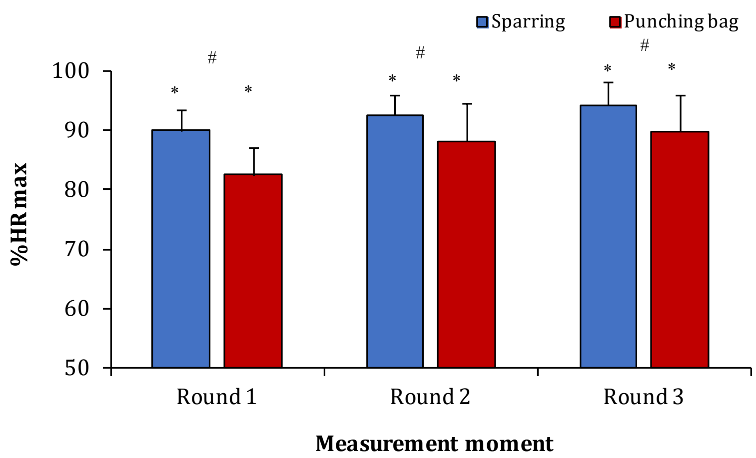


Figure 24: Percent of maximal heart rate response in two boxing activities during three rounds (Adapted from Arsenau, Mekary and Léger [73]).

$\% HR_{max}$ = percent of maximal heart rate; # = different from sparring ($p < 0.05$); * = different between rounds ($1 < 2 < 3$) ($p < 0.05$).

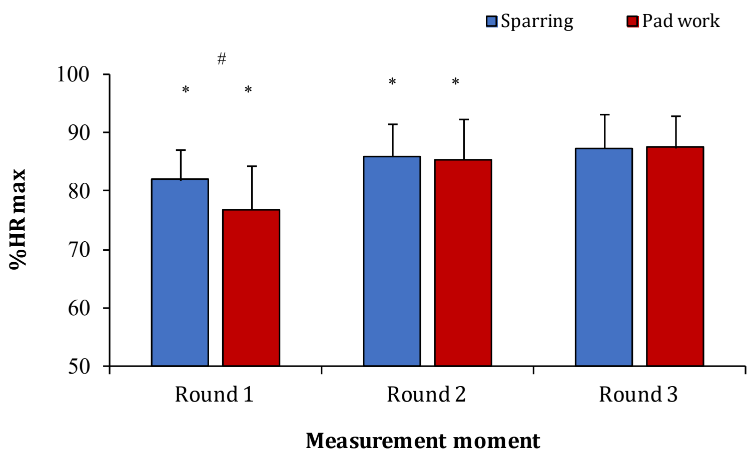
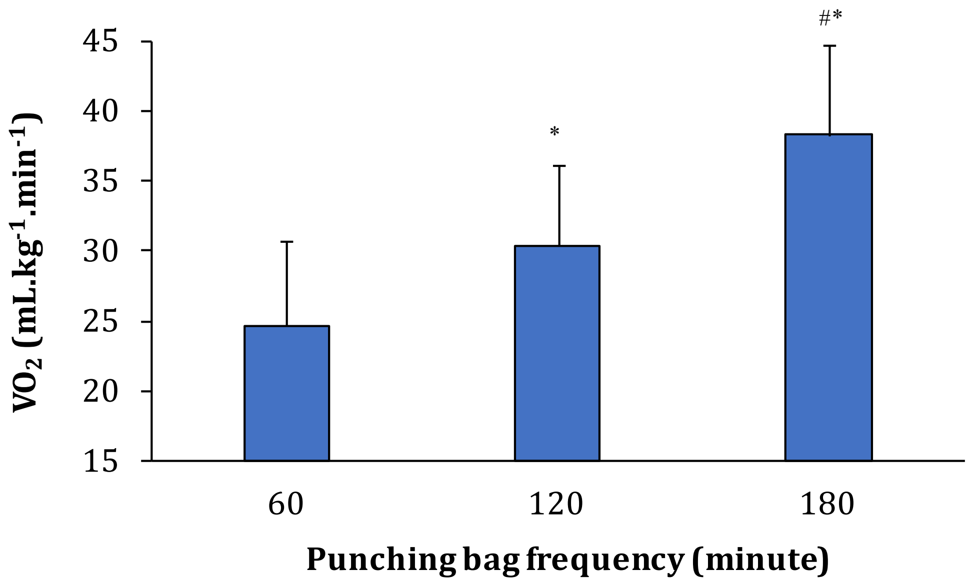


Figure 25: Percent of maximal heart rate response in two activities (sparring and pad work) in three rounds (Adapted from Arsenau, Mekary and Léger [73]).

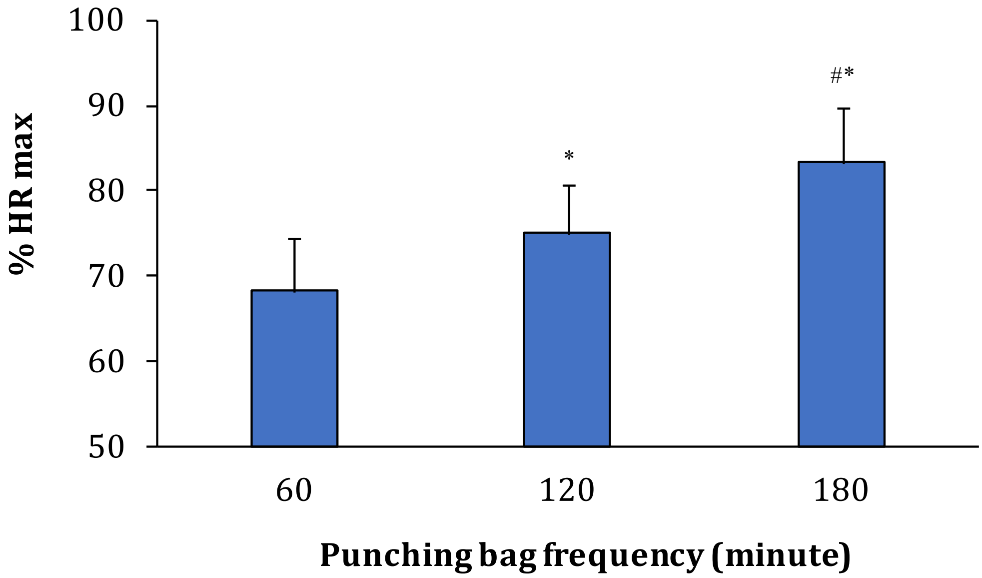
$\%HR_{max}$ = percent of maximal heart rate; # = different from *sparring* ($p < 0.05$); * = different from round 2 ($p < 0.05$).

The authors [73] also observed an effect of type of exercise performed, with the percentage of HR_{max} in sparring (92 ± 4%) being higher than the freely hitting a punching bag activity (87 ± 6%) in the session performed at the gymnasium, while an opposite result was observed for the punches frequency (36 ± 10% and 71 ± 23%, respectively). At the laboratory session, the percentage of HR_{max} was similar between sparring and pad work (86 ± 6% and 84 ± 6%), with the exception of values observed in round 1, in which sparring values were higher than pad work values, and opposite results for punches frequency. Finally, VO_2 peak values from three last activities performed in laboratory (sparring, pad work and freely hitting a punching bag) on 180 punches per minute intensity were similar (43.4 ± 5.9 $ml.kg^{-1}.min^{-1}$; 41.1 ± 5.1 $ml.kg^{-1}.min^{-1}$ and 38.3 ± 6.5 $ml.kg^{-1}.min^{-1}$). Additionally, the VO_2 values increased as the intensity increased (Figure 26) [73]. Increasing intensity also resulted in increase of % HR_{max} values (Figure 27) [73].



* = different from 60 punches per minutes ($p < 0.05$); # = different from 120 punches per minute ($p < 0.05$).

Figure 26: Oxygen consumption response in exercise performed at three intensities (60, 120 and 180 punches per minute) (Adapted from Arsenau, Mekary and Léger [73]).



* = different from 60 punches per minutes ($p < 0.05$); # = different from 120 punches per minute ($p < 0.05$).

Figure 27: Percent of heart rate response in exercise performed at three intensities (60, 120 and 180 punches per minute) (Adapted from Arsenau, Mekary and Léger [73]).

4. Specific tests to control and to monitor progress of the aerobic fitness of combat sports athletes

Evaluation of aerobic fitness involves two main parameters: power and capacity. To assess aerobic power (maximal quantity or rhythm of energy released by the oxidative metabolism per time) VO_{2max} and intensity associated to VO_{2max} (power or speed) are commonly used. To assess aerobic capacity (total energy released by the oxidative system) variables related to anaerobic threshold, as VO_2, HR and intensity associated with the anaerobic threshold are frequently used. Differently from aerobic power that can be measured by maximal indexes, aerobic capacity is not measured directly, *i.e.*, it is measured via association with other submaximal variables (intensity, VO_2 or HR).

Usually tests to evaluate the aerobic fitness involve protocols with progressive load increments, conducted in a treadmill, rowing or cycle ergometers in laboratory conditions. However, given the nature of combat sports, performed with specific technical movements and intermittent characteristics, some tests were developed to consider the specificity of each modality.

4.1. Grappling combat sports

In judo, one of the most used tests to evaluate aerobic and anaerobic fitness in specific situation is the Special Judo Fitness Test (SJFT), proposed by Sterkowicz [17]. This test is performed in three effort periods: 15s (set A), 30s (set B) and 30s (set C) with 10s intervals between them. Two athletes with similar body mass stay positioned in a distance of six meters from each other, and the main objective of the executant is to throw the two partners as many times as possible, performing the *ippon-seoi-nage* technique. Immediately and 1-min after the end of the test, HR is registered. The sum of throws and the HR values are used to calculate the index (Equation 3):

$$\textbf{Index} = \frac{\text{Final HR (bpm)} + \text{HR 1-min after the test (bpm)}}{\text{Number of throws}} \qquad \textbf{(Equation 3)}$$

The best performance in the test represents lower index values, and it is possible to classify the athlete according to each parameter utilized in the test for male (Table 15) [74] and junior and senior female athletes (Table 16 and 17, respectively) [75]. The SJFT, although utilizing a judo-specific movement, has as main limitation the fact that the of number of throws cannot be split, hampering the distinction between an athlete who finished the test immediately after having performed a throw and another who finished the test when he was almost performing a technique.

Table 15: Classification of parameters obtained in Special Judo Fitness Test for male athletes (Adapted from Franchini, Del Vecchio and Sterkowicz [74]).

Classification	Total of throws	HR after (bpm)	HR 1-min after (bpm)	Index
Excellent	≥ 29	≤ 173	≤ 143	≤ 11.73
Good	27 – 28	174 – 184	144 – 161	11.74 – 13.03
Average	26	185 – 187	162 – 165	13.04 – 13.94
Poor	25	188 – 195	166 – 174	13.95 – 14.84
Very poor	≤ 24	≥ 196	≥ 175	≥ 14.85

HR = heart rate.

Table 16: Classification of parameters obtained in Special Judo Fitness Test for female senior athletes (Adapted from Sterkowicz-Prybycien and Fukuda [75]).

Classification	Total of throws	HR after (bpm)	HR 1-min after (bpm)	Index
Excellent	≥ 30	≤ 160	≤ 129	≤ 10.21
Good	29	161 – 170	130 – 138	10.22 – 11.31
Average	26 – 28	171 – 189	139 – 158	11.32 – 13.48
Poor	24 – 25	190 – 199	159 – 167	13.49 – 14.52
Very poor	≤ 23	≥ 200	≥ 168	≥ 14.53

HR = heart rate.

Table 17: Classification of parameters obtained in Special Judo Fitness Test for female junior athletes (Adapted from Sterkowicz-Prybycien and Fukuda [75]).

Classification	Total of throws	HR after (bpm)	HR 1-min after (bpm)	Index
Excellent	≥ 26	≤ 167	≤ 128	≤ 12.18
Good	25	168 – 175	129 – 139	12.19 – 13.71
Average	23 – 24	176 – 190	140 – 161	13.72 – 16.13
Poor	22	191 – 198	162 – 171	16.14 – 17.41
Very poor	≤ 21	≥ 199	≥ 172	≥ 17.42

HR = heart rate.

Franchini et al. [76] estimated the contribution of the three energy systems to supply the energy cost during this test and they observed that 72% of energy released comes from the anaerobic metabolisms (42% from the glycolytic and 30% from the ATP-PCr) and 28% by oxidative metabolism. This test showed a good reproducibility using the intraclass correlation coefficient (ICC) for the following variables: maximal number of throws (ICC = 0.73), HR in the end of the test (ICC = 0.93), HR after 1-min after the test (ICC = 0.89) and index (ICC = 0.89) [77].

Azevedo et al. [78] and Azevedo [79] proposed two tests to evaluate the aerobic capacity in judo. Azevedo et al. [79] developed a specific test in six regional to international level judo athletes, in which athletes performed the technique entrances (*uchi-komi*) applying *ippon-seoi-nage* to determine the anaerobic threshold (lactate minimum test). The test started with 40s of *uchi-komi* and posteriorly with load increments in which athletes performed 8 sets of 1-min with intensities correspondents to 8s, 7s, 6s, 5s, 4s, 3s, 2s and 1s for each entrance. Rhythm of entrance was controlled by a metronome and after each stage, blood lactate was measured. There was no difference between the lactate concentration in the lactate minimum during a running test and the *uchi-komi* test neither between HR at lactate minimum in both tests, suggesting that this kind of test can be used to obtain parameters related to the aerobic capacity. The main limitation of this test involves the cost for its realization because of the multiples analyses of blood lactate.

In turn, Azevedo [79] developed an incremental test, similar to tests usually performed in ergometers. This test involves the realization of specific technical entrance movements (*uchi-komi*) using techniques of *ippon-seoi-nage* in machines (cross-over) adapting the grip in the *judogi*. The velocity of entrance was controlled by a sound signal. Initial load was 1.9 kg with increments of 1.2 kg each 3-min (30s interval between stage to collect blood to analyze the lactate concentration) until the volunteer exhaustion or when athlete could not perform the technique entrance correctly and in the velocity determined previously. To validate this test, the authors also conducted a treadmill maximal incremental test. There was correlation between the intensity correspondent to anaerobic threshold (determined by ventilatory parameters) between general and specific tests ($r = 0.76$; $R^2 = 0.58$; $p = 0.027$), showing that this test also can be used to evaluate the aerobic capacity. Limitations involve the utilization of specific equipment to conduct the test (cross-over), utilization of expensive and refined equipment to determine the anaerobic threshold (gas analyzer) and evaluators with expertise to identify the anaerobic threshold by the ventilatory method.

Although the tests proposed by Azevedo [78] and Azevedo et al. [79] presented some limitations, both bring important information to aerobic capacity training prescription because using these tests it is possible to establish the load correspondent to aerobic capacity. In the study published in 2007 [79] it is possible to prescribe by velocity of technique entrance and in the study published in 2010 [78] by the load (kg) using specific movement.

Santos et al. [16] proposed a test involving specific techniques aiming to determine the aerobic-anaerobic zone transition (anaerobic threshold). In addition, although it was not the main aim of the authors, this test also allows the measurement of VO2max.The authors' interpretation is that the articles which reported the Santos Test results were maximal tests as reported in each of them [16, p.2423, 18, p.144, 82, p. 240]. To realize this test two athletes are needed. The test start with an active phase: three sequences of technique entrance chosen previously by the athlete. In the first technique entrance, the athlete raises his opponent from the floor, in the second the opponent is completely unbalanced and in the third time the athlete can choose between raising or unbalancing the opponent completely. Each set is performed in 40s, with the first set starting with seven repetitions, increasing one repetition each set until the exhaustion (progressive increase of effort). If the athlete could not raise his opponent, put him unbalanced or complete each set in 40s, the test is finished. In the passive phase, two athletes perform movements in the *tatami* with grip in *judogi* during 15s, representing movements that occur during match. Reasons to the test be divided in active and passive phase occur because of intermittent nature of the match. This test has an effort-pause ratio of 40:15s.

The specific test was performed twice to evaluate the reproducibility, and additionally it was performed a treadmill maximal incremental test to validate the test [16] (Table 18). Anaerobic threshold was determined via the individual anaerobic threshold method [80]. Comparing variables related to specific and general tests there was no difference between tests in any variable, confirming validity of the specific test. Regarding reproducibility there was no difference between test and re-test. However, authors did not report the ICC. This study was conducted with 8 athletes from state and national levels, posteriorly a study was conducted with national level athletes (male and female) [81,82] and the findings obtained were similar.

Table 18: Heart rate and oxygen consumption responses in specific and general tests (maximal incremental test) (Adapted from Santos et al. [16]).

	Specific	**General**
Maximal heart rate (bpm)	198 ± 4	200 ± 2
Heart rate in anaerobic threshold (bpm)	170 ± 6	170 ± 3
Heart rate (% heart rate in anaerobic threshold)	86 ± 3	85 ± 2
Maximal oxygen consumption ($ml.kg^{-1}.min^{-1}$)	58 ± 4	60 ± 4

Shiroma et al. [83] developed a judo specific maximal graded exercise test using judo-specific movements (i.e., *hikidashi*, which represents the preparation phase of many judo techniques) carried out on a dojo that could be used to evaluate, prescribe and monitor maximal aerobic speed in judo athletes (UKtest). The initial speed of UKtest is 32 $rep.min^{-1}$ (controlled with metronome) and each stage lasts 1 min with 3 $rep.min^{-1}$ increments. The test is finished when participants can no longer maintain the established speed. The maximal speed reached was defined as maximal aerobic speed and VO_2 was measured throughout the UKtest. VO_{2peak}, HR_{max}, peak blood lactate concentration, rating of perceived effort and maximal aerobic speed were registered. Moreover, the authors conducted a test to confirm that variables measured in UKtest reached maximal values, using a confirmation test. In this test, the procedures described by Nolan, Beaven e Dalleck. [84] were followed: briefly, the athletes performed a time to exhaustion test at 105% of maximal aerobic speed after specific warm-up. Regarding the results, there were no difference in variables measured in UKtest and in confirmation test (Table 19) demonstrating that maximal values are obtained in UKtest.

Table 19: Comparison of physiological and perceptual responses obtained in specific test (UK_{test}) and confirmation test of maximal values obtained (UK_{conf}) (Adapted from Shiroma et al. [83]).

	UK_{test}	**UK_{conf}**	**p**
VO_{2peak} ($mL·kg^{-1}·min^{-1}$)	45.76 ± 6.26	45.16 ± 5.68	0.47
Maximal heart rate (bpm)	186 ± 6	186 ± 6	0.83
Peak blood lactate ($mmol·L^{-1}$)	6.60 ± 2.19	6.35 ± 1.32	0.50
Rating of perceived exertion (a.u.)	18 ± 2	19 ± 1	0.34

a.u. = arbitrary unit; VO_{2peak} = peak oxygen consumption.

In the same study [83], the authors evaluated criterion validity and reliability of this test. The UKtest was performed twice, separated by 7 days, to evaluate the reproducibility, and one upper-body and one lower-body maximal graded test were performed to analyze the criterion validity. Regarding reproducibility there was no difference between test and re-test (Table 20). Comparing variables obtained in UKtest with upper-body and lower-body tests were observed few differences were observed such as longer duration for the UKtest compared to the other two tests, higher VO_{2peak} in the UKtest and lower-body cycle ergometer test compared to the upper-body cycle ergometer test, and lower peak blood lactate in the UKtest compared to the other two tests (Table 21), but very large relationships between values obtained in these tests (Table 22). Therefore, the authors considered that the UKtest is valid and reliable test to evaluate maximal aerobic speed.

Table 20: Comparison of physiological, perceptual and performance responses to *uchi-komi* test (UK_{test}) and *uchi-komi* retest (UK_{retest}) maximal graded exercise (Adapted from Shiroma et al. [83]).

	UK_{test}	UK_{retest}	p
Maximal aerobic speed (rep·min^{-1})	57 ± 3	58 ± 4	0.12
Peak oxygen consumption (mL·kg^{-1}·min^{-1})	46.04 ± 5.34	46.55 ± 4.91	0.57
Maximal heart rate (bpm)	183 ± 5	184 ± 7	0.19
Peak blood lactate (mmol·L^{-1})	7.10 ± 1.76	6.71 ± 1.94	0.53
Rating of perceived exertion (a.u.)	19 ± 1	19 ± 1	1.00

a.u. = arbitrary unit.

Table 21: Comparison of performance, physiological and perceptual responses obtained in specific test (UK_{test}), upper-body (UB_{test}) and lower-body (LB_{test}) maximal graded exercise tests (Adapted from Shiroma et al. [83]).

	UK_{test}	UB_{test}	LB_{test}
Total duration (s)	551 ± 60*†	416 ± 47	433 ± 54
VO_{2peak} (mL·kg^{-1}·min^{-1})	46.04 ± 5.34*	37.03 ± 7.16	44.78 ± 5.98*
Maximal heart rate (bpm)	183 ± 5	178 ± 5	180 ± 8
Peak blood lactate (mmol·L^{-1})	7.10 ± 1.76*†	9.93 ± 2.15	10.29 ± 2.23
Rating of perceived exertion (a.u.)	19 ± 1	20 ± 1	19 ± 1

VO_{2peak} = peak oxygen consumption; a.u. = arbitrary unit; * = different from UB_{test} ($P < 0.05$); † = different from LB_{test} ($P < 0.05$).

Table 22. Relationship (r) between performance, physiological and perceptual responses obtained in specific test (UK_{test}), upper-body (UB_{test}) and lower-body (LB_{test}) maximal graded exercise tests (Adapted from Shiroma et al. [83]).

	UK_{test} vs UB_{test}		UK_{test} vs LB_{test}	
	r	p	r	p
Total duration (s)	0.04	.904	0.38	.228
Peak oxygen consumption (mL·kg^{-1}·min^{-1})	0.78	.003	0.87	<.001
Maximal heart rate (bpm)	0.50	.139	0.68	.035
Peak blood lactate (mmol·L^{-1})	0.54	.084	0.24	.477
Rating of perceived exertion (a.u.)	0.58	.058	0.58	.056

a.u. = arbitrary unit.

As in the tests proposed by Azevedo [79] and Azevedo et al. [78], the test proposed by Santos et al. [16,81,82][1] and by Shiroma et al. [83] also need an expensive and refined equipment (gas analyzer), then the aim is to determine the VO_{2max} and a device to analyze the blood lactate concentration to determine the anaerobic threshold [16,81,82]. The SJFT and UKtest are easier test to execute, although SJFT is a test that only analyze or classify athlete by its index, differently from other tests that allow to establish parameters to training prescription, such as maximal power aerobic index (rhythm of technique entrance, HR_{max} and VO_{2max}) and aerobic capacity by an anaerobic threshold index (rhythm of technique entrance and HR correspondent to the anaerobic threshold). On the other hand, the UKtest allows to establish parameters to evaluate, prescribe and monitor maximal aerobic speed in judo athletes, which could be used together with other tests to prescribe judo-specific high-intensity interval training [86], a method that has been reported to induce expressive aerobic fitness in combat sports athletes, including judo athletes [86]. Here it is worth to highlight that these tests already exist to judo and that validity and reproducibility were confirmed, but until now, there are no tests developed to other grappling combat sports (jiu-jitsu and wrestling).

[1] Although it was not the main aim of the authors of ST, this test also allows the measurement of $VO2_{max}$. In this regard reviewer Luis Santos points out that when the ST is used to determine the VO2max, it must be considered that it is not a maximum effort test (as it was aforementioned, its goal is to determine the aerobic-anaerobic transition zone). The authors' interpretation is that the articles which reported the Santos Test results were maximal tests as reported in each of them: "The test was considered finished when the athletes could no longer meet the previously indicated quality requirements" (16, p. 2423); "The test was considered terminated when the athletes could no longer meet the previously indicated quality requirements." (81, p. 144); "The test was considered finished when the athletes could no longer meet the quality requirements" (82, p. 240).

4.2. Striking combat sports

For striking combat sports, there are two tests to evaluate aerobic fitness in karate and one to taekwondo. Nunan [15] developed a Karate specific test (KSAT) to access maximal aerobic power in five athletes. This test was composed by attack sequences (a leading straight punch, a rear leg roundhouse kick, a rear straight punch and a leading roundhouse kick repeated twice) on a punch bag suspended during 7s as strength as possible with time between attack sequences progressively reduced until athlete could not perform technique sequence in 7s (Table 23).

Table 23: Aerobic fitness evaluation of karate athletes (Adapted from Nunan [15]).

Level	Number of repetition	Activity (s)	Active rest (s)	Exercise total (s)	Accumulative duration (s)
1	10	7	20	270	0
2	6	7	15	132	270
3	6	7	13	120	402
4	6	7	11	108	522
5	6	7	9	96	630
6	6	7	7	84	726
7	6	7	5	72	810
8	6	7	4	66	882
9	6	7	3	60	948
10	6	7	2	54	1008
11	15	7	1	120	1062
Total				**1182**	

The athletes performed this test twice aiming to verify the reliability and they did not observe differences in VO_{2max}, HR_{max} and time to exhaustion values [15]. However, in the second test, peak ventilation was lower (128 ± 14 L/min) than in the first test (130 ± 16 L/min). In addition, it was observed a relationship between time do exhaustion and VO_{2max} attained (R^2 = 0.77). Chaabéne et al. [14] conducted a study with a greater sample size (n = 19) also aiming to evaluate the reproducibility of the test. There were no differences in HR_{max} and time to exhaustion as well as in the Nunan's study [15]. However, the lactate peak was different between tests, with higher values in the first than in the second test. Time to exhaustion presented a small variation between the two tests (3.2%) but it was within the limits of concordance and there was no systematic bias. Typical error was 28.5 s. Moreover, this test was conducted in athletes from two competitive levels (regional and national) to verify if the test would be able to differentiate athletes from different levels. Athletes from national level presented greater time to exhaustion (1032 ± 101s) than regional level (841 ± 134s), peak lactate was higher in national level (6.09 ± 1.78 mmol.L^{-1}) than regional (8.48 ± 2.63 mmol.L^{-1}), while there was no difference for HR_{max} and rating of perceived exertion between national (194 ± 8 bpm; 8 ± 1 a.u.) and regional level (195 ± 9 bpm; 7 ± 1 a.u., respectively). Additionally, through receiver operator characteristics curve (type of analysis to classify individuals in specific groups) this study demonstrated that this test is adequate to classify athletes from different levels.

Later, Chaabéne et al. [87] tested the reproducibility of KSAT. In addition, this study included analysis of capacity of this test to detect modifications in performance, in other words, the amount of change needed to be sure that it is greater than the error of the test. This is important because if the typical error is big, possibly it will not be able to detect small modifications in performance. For HR_{max}, time to exhaustion, lactate peak and rating of perceived exertion there were no differences between the tests. The standard errors of measurement of time to exhaustion within 30s, the smallest worthwhile change was 28s and the minimal detectable change at 95% confidence interval was 81s, showing that to evaluator be 95% right that there was modification in performance this modification will have be greater than 9.4%.

Tabben et al. [18] conducted another study aiming to adapt the specificity of the KSAT considering the small sample size in the previous study of Nunan [15] (n = 5) and effort duration used in Nunan study (7s) which was longer than the standard duration for this modality and lack of standardization of the distance between the athlete and the opponent. In this way, Tabben et al. [18] proposed to verify the validity (which was not tested previously) and the reproducibility of the test (Karate Specific Test - KST). However, with small modifications as: reduction of the effort duration to 3s instead of 7s, fixed distance between the athlete evaluated and the bag (1.5 meters). The effort duration was similar that previous study of Nunan [15], however, recovery interval was decreased each 3-min. In the recovery interval, athletes could exercise to reproduce the competition (Table 24).

Table 24: Aerobic fitness evaluation of karate athletes (Adapted from TABBEN et al. [18]).

Level	Number of repetition	Activity (s)	Active rest (s)	Exercise total (s)	Accumulative duration (s)
1	2	3	42	90	90
2	3	3	27	90	180
3	4	3	20	92	272
4	5	3	15	90	362
5	6	3	12	90	452
6	7	3	10	91	543
7	8	3	8	88	631
8	11	3	5	88	719
9	15	3	3	90	809
10	18	3	2	90	899

In relation to the reproducibility, there was no difference between test and retest for any variable investigated. VO_{2peak} and time to exhaustion presented a typical error of about 5%, HR_{max} and peak lactate ≤ 5% and rating of perceived exertion of 2.4%. The minimal detectable change for VO_{2peak} was 1.39 ml.kg^{-1}.min^{-1} and for time to exhaustion was 6.15s, showing that to evaluator be 95% right that the modification was due to performance alterations changes of about 2.58% in VO_{2peak} and of 1% in time to exhaustion are necessary. Considering the validity of this test, a significant correlation between the VO_{2peak} in laboratorial test and the time to exhaustion in KST test was found (r = 0.81). HR_{max} and VO_{2peak} was not different between the KST (196 ± 11 bpm; 55.1 ± 4.8 ml.kg^{-1}.min^{-1}) and the laboratorial test (194 ±10 bpm; 53.2 ± 6.6 ml.kg^{-1}.min^{-1}). Table 25 presents variables analyzed in the KSAT and KST from different investigations.

Table 25: Variables analyzed in Karate specific test and retest by different investigations.

Variables	Test	Retest	ICC
Nunan [15]			
HR_{max} (bpm)	191 ± 7	188 ± 7	NR
VO_{2max} (ml.kg^{-1}.min^{-1})	48.9 ± 11.4	49.9 ± 12.5	NR
Time to exhaustion (s)	1065 ± 98	1093 ± 106	NR
Chaabène et al. [14]			
HR_{max} (bpm)	169 ± 9	194 ± 9	NR
Time to exhaustion (s)	871 ± 150	881 ± 158	0.98
Peak lactate (mmol.L^{-1})	9.12 ± 2.59	8.05 ± 2.67*	NR
Rating of perceived exertion (a.u.)	8 ± 1	8 ± 1	NR
Chaabène et al. [87]			
HR_{max} (bpm)	197 ± 8	195 ± 8	NR
Time to exhaustion (s)	871 ± 150	881 ± 158	0.98
Peak lactate (mmol.L^{-1})	9.0 ± 2.6	8.3 ± 3.0	NR
Rating of perceived exertion (a.u.)	8 ± 1	8 ± 1	NR
Tabben et al. [18]			
VO_{2max} (ml.kg^{-1}.min^{-1})	53.7 ± 5.1	54.0 ± 5.0	0.99
Time to exhaustion (s)	635 ± 50	636 ± 49	0.99
Peak lactate (mmol.L^{-1})	10.8 ± 2.6	10.5 ± 2.4	0.90

* = different from test; HR_{max} = maximal heart rate; VO_{2max} = maximal oxygen consumption; ICC = intraclass correlation coefficient; NR = not reported.

For karate, there is only one test developed until now that was firstly created by Nunan [15] (KSAT) and tested by Chaabène et al. [14,87] and posteriorly adapted by Tabben et al. [18]. This test gives an indicative of the maximal aerobic power (VO_{2max}, rhythm of technique entrance and HR_{max}). This test has its validity and reproducibility confirmed. However, there is no indicative of the aerobic capacity, and it is required a gas analyzer and the measurement of blood lactate during its execution, which can be of difficulty access for most of the coaches.

For taekwondo, Sant'Ana et al. [88] developed a maximal incremental test (progressive specific taekwondo test - PSTT), in which athletes perform kicks (*bandal tchagui*) in height between the umbilical scar and xiphoid process of the athlete. This height is marked with a taekwondo vest, around the bag. Athletes perform kicks alternating legs and start the protocol always kicking first with the right leg. The test begins with 100s effort duration and the frequency of six kicks. In each stage the athlete had to perform four more kicks and the duration of each stage decreases over the test (Table 26). This test is conducted until voluntary exhaustion or when the athlete cannot perform the stablishes kick frequency or when he/she cannot reach the height previously fixed for the kick. The main aim of this study was to access the HR_{max}, HR deflection point, maximal frequency of kicks, and frequency of kicks corresponding to the deflection point and peak lactate. Post-test they performed constant load tests composed by three sets of 4-min (one bellow the HR deflection point, one at the HR deflection point and one above the HR deflection point) with 1-min passive interval recovery between each set. Moreover, lactate concentration was measured [88]. HR deflection point was identified in all athletes, being at 94% of HR_{max} and kick frequency related to deflection point represented 55% of maximal kick frequency (18 ± 3). In the constant load test below the kick frequency related to the HR deflection point HR was 86 ± 6% of HR_{max} and lactate concentration was 3.2 ± 0.78 $mmol.L^{-1}$. In the kick frequency related to the HR deflection point HR was 91 ± 1% of HR_{max} and lactate concentration was 3.82 ± 0.72 $mmol.L^{-1}$; above the HR deflection point HR was 95 ± 8 % of HR_{max} and lactate concentration was 5.93 ± 0.93 $mmol.L^{-1}$ [16].

Table 26: Aerobic fitness evaluation of taekwondo athletes (Adapted from Sant'ana et al. [88]).

Stages	Duration (s)	Accumulated adjusted duration (s)	Frequency of kicks
1	100	100	6
2	84	180	10
3	77.1	260	14
4	73.3	330	18
5	70.9	405	22
6	69.2	470	26
7	68.0	540	30
8	67.1	605	34
9	66.3	675	38
10	65.7	740	42
11	65.2	805	46
12	64.8	870	50

Posteriorly, to validate the PSTT a treadmill maximal incremental test was executed [89] (Table 27) in eight taekwondo athletes. Comparing variables related to specific and general tests no differences were found for VO_{2peak}, VO_2 at HR deflection point and HR at HR deflection point between tests, but higher HR_{peak} and peak lactate values were found in the treadmill test compared to the PSTT. Furthermore, 95% limits of agreement indicated that the differences between the two measures can reach 11% for VO_{2peak} and 17% for VO_2 at HR deflection point. The authors considered the PSTT a valid tool to asses aerobic power and capacity in taekwondo athletes.

Table 27: Heart rate and oxygen consumption responses in specific (progressive specific taekwondo test) and general tests (maximal incremental test) (Adapted from Sant'ana et al. [89].

Variables	Specific	General	*p*	Absolute and relative limits of agreement
VO_{2peak} ($ml.kg^{-1}.min^{-1}$)	49.2 ± 5.3	50.5 ± 4.4	0.054	5 (11%)
VO_2 at HRDP ($ml.kg^{-1}.min^{-1}$)	43.6 ± 5.5	42.8 ± 4.7	0.374	7 (17%)
HR_{peak} (bpm)	190 ± 8	192 ± 10	0.001	7 (4%)
HRDP (bpm)	172 ± 8	169 ± 8	0.138	12 (7%)
Peak lactate ($mmol.L^{-1}$)	8.9 ± 1.7	11.1 ± 2.3	0.000	4 (39%)

VO_{2peak} = peak oxygen consumption; HRDP = heart rate deflection point; HR_{peak} = peak heart rate.

Still concerning the PSTT, Sant'Ana et al. [90] conducted a study to determine an equation to estimate the absolute and relative VO2peak in twenty-two black belt taekwondo athletes. The independent variables maximal frequency of kicks (FK_{MAX}), height and HR deflection point. Two significant regression equations were obtained: (1) VO_{2peak} absolute (L.min−1) = 7.230 - 0.029 (HR deflection point) + 0.048 (FK_{MAX}), adjusted R^2 = 0.314, and SEE = 0.428; and (2) VO_{2peak} relative ($mL.kg^{-1}.min^{-1}$) = 28.946 + 0.761 (FK_{MAX}) - 0.030 (height), adjusted R^2 = 0.322, and SEE = 4.665. Although the equations were significant, they presented an explained variance of 31-32%, that is, approximately 70% of variation in VO_{2peak} values could not be explained by the equations.

Araujo et al. [91] developed a taekwondo specific exercise test using sport-specific movements (Roundhouse kick - *dolio-tchagi*) to asses variables related to maximal aerobic speed and aerobic-anaerobic thresholds (ventilatory thresholds) (TKDtest) and compared these variables with treadmill exercise test in taekwondo athletes. After the 5 min warm-up (consisted of free Taekwondo displacements and kicks, wearing the full test equipment, with an intensity zone ranging between 100 and 120 beats per minute) the test is started. The initial speed of TKDtest is 10 rep.min-1 (alternating the legs) and each stage last 1 min with 3 rep.min-1 increments. The test is finished when participants can no longer maintain the established speed or when at least three of four previously established criteria were achieved: 1) maximum perception of effort as reflecting assign 10 in adapted Borg's scale; 2) heart rate ≥ 90% of predicted HR_{max} (220-age) or presence of a HR plateau (ΔHR in two consecutive work rates < 4 $bpm.min^{-1}$); 3) presence of a VO2 plateau (ΔVO_2 in two consecutive work rates < 2.1 $ml.kg^{-1}.min^{-1}$); 4) a gas exchange ratio > 1,1. Regarding the results (Table 28), a difference was observed in VO_2R (difference between VO_2 and VO_2 in rest). Therefore, the authors considered that the UKtest is valid and reliable test to evaluate maximal aerobic speed and aerobic-anaerobic thresholds.

Table 28: Comparison of heart rate and oxygen consumption responses in specific (TKDtest) and general tests (treadmill maximal incremental test) (Adapted from Araujo et al. [91]).

	TKDtest	Treadmill test	p	ICC (p)
VO_{2peak} ($ml.kg^{-1}.min^{-1}$)	47.36 ± 5.40	49.60 ± 5.34	0.06	0.855 (0.003)
VO_2 at VT1 ($ml.kg^{-1}.min^{-1}$)	40.02 ± 6.71	42.73 ± 5.74	0.17	0.709 (0.030)
VO_2 at VT2 ($ml.kg^{-1}.min^{-1}$)	42.24 ± 7.95	42.67 ± 5.42	0.77	0.84 (0.003)
VO_2 at rest ($ml.kg^{-1}.min^{-1}$)	3.76 ± 1.29	3.64 ± 0.59	0.71	NR
VO_2 reserve ($ml.kg^{-1}.min^{-1}$)	43.59 ± 5.76	45.96 ± 5.46	0.03	NR
HR_{peak} (bpm)	187 ± 6	189 ± 7	0.29	0.594 (0.086)
HR at VT1 (bpm)	173 ± 7	171 ± 9	0.41	0.388 (0.194)
HR at VT2 (bpm)	175 ± 12	180 ± 6	0.18	0.364 (0.213)
HR at rest (bpm)	65 ± 6	62 ± 8	0.16	NR
HR reserve (bpm)	121 ± 7	127 ± 12	0.29	NR
Time at peak (s)	495.74 ± 85.01	512.36 ± 184.28	0.76	NR

ICC= Intraclass correlation coefficient; VO_2 = oxygen consumption; HR = heart rate; VT = ventilatory threshold; NR= not reported.

Araujo et al. [92], in other study, developed an interval taekwondo specific exercise test using the same sport-specific movements (Roundhouse kick - *Dolio-Tchagi*) used in a previous study [91] to asses variables related to maximal aerobic speed and aerobic-anaerobic thresholds (ventilatory thresholds) (ITKDtest). Additionally, the authors compared these variables with TKDtest (continuous) and treadmill exercise test in taekwondo athletes. After the 5 min warm-up (consisted of free Taekwondo displacements and kicks, wearing the full test equipment, with an intensity zone ranging between 100 and 120 beats per minute) the test is started. The initial speed of TKDtest is 30 rep.min-1 (alternating the legs) and each stage lasts 2 min with 10 $rep.min^{-1}$ increments with a period of passive recovery lasting 1 min. The same criteria described by Araujo et al. [91] were followed to establish the end of the test. Regarding the results presented in Table 29, the authors suggested that ITKDtest may be used for VO_{2peak}, VO_2 at VT1 and VT2, and HR_{peak}, whereas TKDtest seems more appropriate method to assess VO_2 and HR at VT1 and VT2.

Table 29: Comparison of heart rate and oxygen consumption responses in specific interval (ITKDtest), continuous (TKDtest) taekwondo-specific and general tests (treadmill maximal incremental test) (Adapted from Araujo et al. [92]).

	ITKDtest	TKDtest	Treadmill test	p
VO_{2peak} (ml.kg⁻¹.min⁻¹)	46.91 ± 5.30	48.42 ± 6.07	49.91 ± 5.09	0.023*
VO_2 at VT1 (ml.kg⁻¹.min⁻¹)	34.87 ± 6.25	40.27 ± 7.00	42.73 ± 5.86	<0.001†‡
VO_2 at VT2 (ml.kg⁻¹.min⁻¹)	36.34 ± 7.97	43.48 ± 8.19	42.06 ± 5.74	0.005†‡
VO_2 at rest (ml.kg⁻¹.min⁻¹)	3.35 ± 0.53	3.71 ± 1.25	3.51 ± 0.39	0.379
VO_2 reserve (ml.kg⁻¹.min⁻¹)	43.62 ± 5.17	44.71 ± 6.39	46.39 ± 5.06	0.019*
HR_{peak} (bpm)	190 ± 5	189 ± 6	191 ± 7	0.346
HR at VT1 (bpm)	165 ± 12	173 ± 7	171 ± 9	0.084
HR at VT2 (bpm)	165 ± 16	177 ± 12	182 ± 7	0.001†
HR at rest (bpm)	65 ± 8	66 ± 6	63 ± 8	0.317
HR reserve (bpm)	125 ± 8	123 ± 7	128 ± 10	0.172

ICC= Intraclass correlation coefficient; VO_2 = oxygen consumption; HR = heart rate; VT = ventilatory threshold; NR= not reported; *= difference between treadmill test and ITKDtest ($p \leq 0.05$); †= difference between treadmill test and TKDtest ($p \leq 0.05$); ‡= difference TKDtest and ITKDtest ($p \leq 0.05$).

Da Mota et al. [93] conducted two kinds of tests to identify the anaerobic threshold using taekwondo-specific technique. The first test was composed by 2-min stages interspersed by 1-min recovery for blood lactate analysis. The first stage started with 15 kicks.min^{-1} and there was increase of 15 kicks per stage and velocity of each kick was controlled by metronome. The test was finished by voluntary exhaustion or when the athlete could not perform more kicks. The other test was equal, however it started with hyperlactatemia (elevated lactate levels – lactate minimum method to determine anaerobic threshold). There was no difference in the number of kicks between the lactate minimum method (71 ± 11 kicks.min^{-1}) and the other one (60 ± 17 kicks.min^{-1}).

For taekwondo, there are already four tests available [88,91,92,93], which provide indexes related to the aerobic capacity of kick frequency at the HR deflection point [88], anaerobic threshold [93] and index about the aerobic power of maximal kick frequency in continuous [88,91,92] and interval [92] tests. The PSTT, TKDtest and ITKDtest have their validity confirmed [89,91,92]. However, validity was not verified in one test [93] and reproducibility were not verified for any test.

5. Longitudinal studies aiming development of aerobic fitness in combat sports athletes

Long-term studies involving combat sports are still scarce when compared with information in other sports such as soccer, basketball, rugby or cyclical activities as cycling, running, rowing or swimming. Although information available are still incipient, it can be noted that this kind of investigation has risen since 2009. Thus, this topic presents studies published aiming to evaluate the development of aerobic fitness in response to long-term training program in combat sports athletes.

5.1. Grappling combat sports

Kim et al. [31] submitted elite level judo athletes to 8 weeks of high-intensity intermittent training, four times a week, 30s effort at 80-90% of maximal aerobic velocity by 4-min recovery in treadmill. Six sets were performed in the weeks 1 and 2, 8 sets in the weeks 3 and 4, and 10 sets in weeks 5 to 8. Before and after the training period a treadmill maximal incremental test and one simulated match were performed. After four and eight weeks, there was no difference in VO_{2max}, HR_{max} obtained in the treadmill maximal incremental test and HR after judo match.

Borowiak et al. [94] submitted nine judo athletes to a 5-week training program composed of low-intensity exercises (continuous runs, tactical and technical skills, *uchi-komi* in place, *jaku-soku-geiko* in motion, and strength training; HR < 150 bpm); moderate-intensity (runs and forced marches in the mountains, tactical and technical skills with set pace, *uchi-komi*, *randori,* and *sute-geiko*; HR = 151-171 bpm), and high-intensity intermittent exercise (sprint runs – 60, 100 and 300 m, sparring fights, circuit training, and *uchi-komi*; HR > 171 bpm). There was an increase in the velocity corresponding to the anaerobic threshold while the HR associated with the anaerobic threshold was not modified.

Farzad et al. [95] added to the traditional training of wrestling athletes (seven from national level and six from regional level) a high-intensity intermittent training (six sets of 35 meters performing maximal efforts interspersed by 10s intervals), twice a week, during four weeks. In the first week, three sets were performed with 3-min of recovery interval between sets. A control group performed only traditional training. Before and after training period athletes had the aerobic fitness (VO_{2max}, velocity associated to $VO_{2máx}$, maximal ventilation and time to exhaustion in maximal intensity) evaluated. Only the trained group improved VO_{2max} (5.4%) and the time to exhaustion (32%).

Sterkowicz et al. [96] submitted five judo athletes to a training program during six weeks. During week 1 and 2 athletes performed training to improve the aerobic fitness (running and rowing performed continuously and intermittently), resistance training and combats with emphasis in tactical skill, every day. In weeks 3 and 4, they performed *randori* two times a week and sparring three times a week aiming at strength and aerobic fitness development. In weeks 5 and 6 they performed training to preparation for competition and it was oriented towards the development of speed and speed endurance. There was no difference in variables analyzed (VO_{2max}, HR_{max}, $\%VO_2$ at anaerobic threshold, % HR at anaerobic threshold), showing that the training employed did no modify variables related to aerobic fitness in maximal incremental test.

Bonato et al. [97] investigated if the inclusion of a high-intensity intermittent training into a judo traditional training program, could improve aerobic fitness (maximal incremental test) in elite athletes (6 men and 3 women). For this, athletes were submitted to 12 weeks of training. Athletes performed training once a week that was composed by 15 effort periods with duration of 1-min at 90% of the maximal velocity attained in maximal incremental test, interspersed by 1-min passive recovery. At the final of training period, authors reported increase of the maximal velocity attained in the incremental test and VO_2 correspondent to the anaerobic threshold (*V slope* method) and no changes in VO_{2max}. Moreover, the authors reported a decrease of HR (-17%) and VO_2 (-22%) recovery (post-maximal incremental test) and greater SJFT index (12%).

Franchini et al. [98] divided 35 judo athletes in a control group (n = 8) and three groups of high-intensity intermittent training twice a week for 4 weeks (2 blocks of ten 20s all-out effort by 10s interspersed by 5-min of passive pause). Each group performed a different type of workout: the lower-body group performed the HIIT using a lower-body cycle ergometer with 4.5% of body mass as resistance; the upper-body group performed HIIT in an upper-body bicycle and the load used was 3% of body mass; the specific group was submitted to *uchi-komi* (technique entrance), throwing the partner at the end of each set. Pre and post-training period, the authors tested the aerobic power and capacity in upper and lower-body ergometer (incremental test). Upper-body trained group improved the maximal aerobic power in the upper-body incremental test, and the lower-body group improved the power at OBLA (onset blood lactate accumulation – a method to evaluate aerobic capacity). In a complementary study with the same design, Franchini et al. [99] analyzed the effect of the same training program in judo-specific tasks, including the SJFT. The authors verified an increase in the number of throws in the SJFT for the upper-body training group, a decrease in HR immediately after the SJFT for the lower-body training group and in SJFT index for *uchi-komi* group.

In relation to improvement of aerobic capacity, Borowiak et al. [94] reported improvement of the velocity correspondent to the AnT, Bonato et al. [97] reported improvement of the VO_2 correspondent to the AnT, and Franchini et al. [98] reported an improvement in the power correspondent to OBLA for the lower-body group. An improvement of aerobic power was showed by Farzad et al. [95] (VO_{2max} and Tlim), Bonato et al. [97] (SJFT index and V_{max} attained in the maximal incremental test) and Franchini et al. [98,99] (maximal aerobic power in upper-body incremental test and a decrease in HR immediately after the SJFT for the lower-body training group and in SJFT index for *uchi-komi* group).

Kim et al. [31] did not show any improvement of aerobic power. This study had a good design using a control group, they detailed how loads were employed during the training, days of week, type of movement, used both general (incremental test) and specific (match simulation) evaluations and observed parameters that in fact indicate aerobic fitness (HR and VO_{2max}). However, maybe the training protocol chosen was not adequate to improve aerobic fitness because 30s efforts by 4-min recovery may benefit more the anaerobic fitness. Bonato et al. [97] also used a good design, however they added high-intensity intermittent exercise once a week, which may not have been enough to generate improvements in VO_{2max}, but generated an increase in the maximal velocity attained in the maximal incremental test. In addition, they reported improvement in recovery HR and VO_2 kinetic off, that can be interesting in competition situation (multiple matches) because this kind of training was able to optimize recovery. In Borowiak et al. [94] and Sterkowicz et al. [96] studies there was a very limited description about the training program, especially concerning intensity control which limits the application and understanding of how this kind of training could affect aerobic fitness. Franchini et al. [98,99] studies used a good design, comparing general and specific movements for training and evaluation, but a small sample for each group may have limited the comparisons and findings.

Table 30 presents results from long-term studies in relation to aerobic fitness improvement in grappling combat sports.

Table 30: Aerobic fitness pre and post a training program.

	Group	Pre	Post
Kim et al. [31]			
VO_{2max} (ml.kg^{-1}.min^{-1})	Experimental	49.8 ± 4.1	53.12 ± 4.8
	Control	46.6 ± 5.0	50.1 ± 4.3
HR_{max} (bpm)	Experimental	181 ± 1	178 ± 4
	Control	180 ± 7	179 ± 7
HR post-match (bpm)	Experimental	177 ± 9	176 ± 8
	Control	172 ± 7	172 ± 7
Farzad et al. [95]			
VO_{2max} (ml.kg^{-1}.min^{-1})	Experimental	49.3 ± 4.4	52.0 ± 3.4$^{\#}$
	Control	51.2 ± 6.1	50.1 ± 4.7
S_{max} (km.h^{-1})	Experimental	16.0 ± 1.0	16.5 ± 0.9
	Control	16.5 ± 1.6	15.8 ± 1.0
Tlim on VO_{2max} (s)	Experimental	356.5 ± 95.1	471.2 ± 128.6$^{\#}$
	Control	326.4 ± 97.1	322.0 ± 89.4
Borowiak et al. [94]			
S_{AnT} (km.h^{-1})	Experimental	10.6 ± 1.7	12.2 ± 1.0$^{\#}$
HR_{AnT} (bpm)	Experimental	163 ± 17	169 ± 13
Sterkowicz et al. [96]			
VO_{2max} (ml.kg^{-1}.min^{-1})	Experimental	64.0 ± 2.6	62.8 ± 4.2
% VO_{2AnT}	Experimental	74.7 ± 5.0	76.1 ± 3.5
HR_{max} (bpm)	Experimental	197 ± 8	196 ± 11
%HR_{AnT}	Experimental	85.8 ± 2.9	84.9 ± 6.4
SJFT index	Experimental	11.39 ± 1.24	11.38 ± 1.33
Bonato et al. [97]			
VO_{2max} (ml.kg^{-1}.min^{-1})	Experimental	47.7 ± 7.3	50.0 ± 4.5
AnT (% VO_{2max})	Experimental	74.4 ± 1.2	79.8 ±5.9$^{\#}$
S_{max} (km.h^{-1})	Experimental	13.4 ± 1.2	14.0 ± 1.5$^{\#}$
SJFT index	Experimental	13.75 ± 0.77	12.24 ± 1.18*
HR immediately after SJFT (bpm)	Experimental	184 ± 7	177 ± 15*
HR after 1-min SJFT (bpm)	Experimental	155 ± 15	145 ± 15
Franchini et al. [98]			
Upper-body maximal graded test			
MAP	LBTG	136 ± 15	143 ± 14
	UBTG	146 ± 18	164 ± 15$^{\#}$
	UKTG	139 ± 25	149 ± 17
	Control	120 ± 20	117 ± 28
VO_{2peak} (L.min^{-1})	LBTG	2.78 ± 0.41	3.03 ± 0.39

	UBTG	3.10 ± 0.70	3.22 ± 0.58
	UKTG	3.16 ± 0.30	3.27 ± 0.33
	Control	2.86 ± 0.37	2.72 ± 0.83
HR_{max} (bpm)	LBTG	180 ± 11	183 ± 18
	UBTG	179 ± 11	179 ± 20
	UKTG	180 ± 7	178 ± 12
	Control	169 ± 9	169 ± 15
Power at OBLA (W)	LBTG	68 ± 22	83 ± 14#
	UBTG	82 ± 21	95 ± 27
	UKTG	66 ± 15	72 ± 12
	Control	74 ± 26	71 ± 21
VO_2 at OBLA ($L.min^{-1}$)	LBTG	1.80 ± 0.35	2.14 ± 0.53
	UBTG	1.94 ± 0.40	2.00 ± 0.51
	UKTG	1.79 ± 0.32	1.75 ± 0.28
	Control	2.06 ± 0.35	2.06 ± 0.45
Lower-body maximal graded test			
MAP	LBTG	240 ± 28	251 ± 49
	UBTG	259 ± 43	254 ± 39
	UKTG	252 ± 37	255 ± 36
	Control	217 ± 34	217 ± 35
VO_{2peak} ($L.min^{-1}$)	LBTG	3.62 ± 0.50	3.68 ± 0.80
	UBTG	3.82 ± 0.59	3.86 ± 0.44
	UKTG	3.87 ± 0.44	3.74 ± 0.36
	Control	3.56 ± 0.49	3.54 ± 0.74
HR_{max} (bpm)	LBTG	179 ± 8	180 ± 13
	UBTG	183 ± 9	185 ± 18
	UKTG	181 ± 12	178 ± 10
	Control	174 ± 9	169 ± 23
Power at OBLA (W)	LBTG	150 ± 15	149 ± 38
	UBTG	160 ± 35	163 ± 24
	UKTG	136 ± 31	148 ± 17
	Control	142 ± 22	138 ± 23
VO_2 at OBLA ($L.min^{-1}$)	LBTG	2.24 ± 0.24	2.19 ± 0.52
	UBTG	2.23 ± 0.56	2.47 ± 0.37
	UKTG	2.10 ± 0.29	2.12 ± 0.27
	Control	2.53 ± 0.33	2.49 ± 0.46
Franchini et al. [99]			
Number of throws in the SJFT (rep)	LBTG	27 ± 3	27 ± 3
	UBTG	25 ± 2	27 ± 2#
	UKTG	25 ± 3	26 ± 2
	Control	25 ± 3	24 ± 2
HR immediately after SJFT (bpm)	LBTG	181 ± 9	174 ± 9*
	UBTG	175 ± 11	177 ± 13
	UKTG	180 ± 8	175 ± 9
	Control	176 ± 2	173 ± 11
HR after 1-min SJFT (bpm)	LBTG	152 ± 10	150 ± 13
	UBTG	142 ± 22	144 ± 13
	UKTG	152 ± 14	140 ± 12
	Control	146 ± 16	150 ± 11
SJFT index ($beats.min^{-1}$ $throw^{-1}$)	LBTG	12.68 ± 1.99	12.04 ± 1.75
	UBTG	12.84 ± 2.55	12.08 ± 1.35
	UKTG	12.84 ± 1.47	12.07 ± 1.36*
	Control	13.11 ± 1.49	13.80 ± 1.14

VO_{2max} = maximal oxygen consumption; HR_{max} = maximal heart rate; V_{max} = maximal velocity; Tlim = time limit; V_{AnT} = velocity correspondent to the anaerobic threshold; HR_{Lan} = heart rate correspondent to the anaerobic threshold; AnT = anaerobic threshold; SJFT = Special Judo Fitness Test; MAP = maximal aerobic power; VO_{2peak} = peak oxygen consumption; LBTG = lower-body training group; UBTG = upper-body training group; UKTG = *uchi-komi* training group; OBLA = onset blood lactate accumulation; * = lower than pre-training ($p < 0.05$); # = higher than pre-training ($p < 0.05$).

5.2. Striking combat sports

Ravier et al. [100] added a high-intensity intermittent exercise composed by 7-9 sets of 20s in the intensity correspondent to 140% of velocity correspondent to VO_{2max} with interval recovery of 15s between sets to a Karate training program (n = 9 athletes de national level), while another group (n = 8) did not performed any additional training program. When athletes completed more than nine sets, there was a load increment of 5%. Before and after seven weeks, the athletes were submitted to a maximal incremental test and a supramaximal test to exhaustion. After the training period there were no changes in the control group while in the HIIT group improvements in the time to exhaustion (23.6%) and VO_{2max} (4.6%) were observed.

El-Ashker and Nasr [101] submitted 17 elite boxers from Egypt to a training program composed by 8 weeks, in which athletes performed 32 sessions (four times by week) divided into three phases: 1st phase – development of physical fitness components as well as developing fundamental motor skills; 2nd phase – develop specific physical fitness components and enhance advanced technical skills alongside competition experience; 3rd phase – to adjust technical performance, train for the main competition in addition to emphasizing tactical and competition experience, in three intensities organized as presented in the table below (Table 31). Before and after the training program athletes were submitted to a treadmill maximal incremental test in which VO_{2max}, HR_{max}, HR after 1, 2 and 3-min recovery, moreover, it was analyzed HR at rest were evaluated. There were decreases of HR at rest and HR at recovery after 1-, 2- and 3-min, while other variables increased from pre to post-training.

Table 31: Description of training program (number of weeks, duration and intensity of the sessions) in three phases (basic, specific and taper) (Adapted from El-Ashker and Nasr [101]).

	Phase 1 - basic	**Phase 2 - specific**	**Phase 3 - *taper***
Number of weeks	2	3	3
Sessions duration (min)	110	100	90
Intensity (%)*	70	80	90

* = intensity calculated from Karvonen equation [$(HR_{max} - HR_{rest}$ * (% of intensity aimed) + FC_{rest}], being HR_{max} = 220 - age.

Kamandulis et al. [102] divided 18 male amateur boxers in an experimental group that performed an additional training composed by 3 rounds of 14 sets of 3s all-out punching bouts (10s of recovery between rounds, three times a week for four weeks) and in a control group (that kept normal training during preparatory period and the same 3 rounds at low-intensity). Before and after the training period, an upper-body incremental test was performed to evaluate the maximal aerobic power and VO_{2peak}. After the training period, the experimental group showed an increase in VO_{2peak} and maximal aerobic power while no difference was observed in these variables for the control group.

Monks et al. [103] divided 33 elite male and female taekwondo athletes (with 7 years experience) into two groups (high-intensity intermittent training and moderate-intensity continuous training groups) that performed 11 sessions over 4 weeks (3 times a week during first three weeks and twice a week in fourth week). The high-intensity intermittent training group performed approximately 1 to 3 sets of running varying between 6 to 20 efforts with duration between 30 and 60s at 85 to 100% of HRmax interspersed by 60 to 120s of active recovery periods walking; the moderate-intensity continuous training group performed 5 kilometers at 85% of HR_{max}. Sessions were performed in the outdoor tracking. After four weeks, an incremental test (Bruce protocol) was applied to measure aerobic fitness. Both groups increased VO_{2max} and decreased HR_{max} in the incremental test.

Table 32 presents results from long-term studies in relation to aerobic fitness improvement in striking combat sports.

Table 32: Aerobic fitness pre and post a training program.

	Group	Pre	Post
Ravier et al. [100]			
VO_{2max} (ml.kg^{-1}.min^{-1})	Experimental	58.7 ± 3.1	61.4 ± 2.6$^{\#}$
	Control	58.2 ± 3.1	58.1 ± 4.4
Tlim at 140% VO_{2max} (s)	Experimental	115.5 ± 20.7	142.8 ± 36.9$^{\#}$
	Control	135.7 ± 28.8	128.8 ± 20.9
El-Ashker and Nasr [101]			
HR_{rest} (bpm)	Experimental	73 ± 3	67 ± 2*
HR_{max} (bpm)	Experimental	197 ± 6	204 ± 7$^{\#}$
HR 1-min of recovery (bpm)	Experimental	171 ± 7	166 ± 5*
HR 2-min of recovery (bpm)	Experimental	146 ± 7	141 ± 7*
HR 3-min of recovery (bpm)	Experimental	139 ± 7	128 ± 5*
VO_{2max} (ml.kg^{-1}.min^{-1})	Experimental	58.2 ± 6.9	64.6 ± 7.2$^{\#}$
Kamandulis et al. [102]			
VO_{2max} (ml.kg^{-1}.min^{-1})	Experimental	33.19 ± 1.29	40.74 ± 1.29$^{\#}$
	Control	34.88 ± 2.33	35.12 ± 1.45
MAP (W)	Experimental	175 ± 12	188 ± 7$^{\#}$
	Control	195 ± 13	193 ± 7
Monks et al. [103]			
VO_{2max} (ml.kg^{-1}.min^{-1})	HIIT	56.1 ± 1.4	60.8 ± 1.6$^{\#}$
	MICT	51.4 ± 1.3	52.4 ± 1.5$^{\#}$
HR_{max} (bpm)	HIIT	186 ± 2	179 ± 3*
	MICT	184 ± 2	178 ± 2*
Incremental test duration (min)	HIIT	14.7 ± 0.2	15.1 ± 0.3
	MICT	13.4 ± 0.2	13.4 ± 0.3

VO_{2max} = maximal oxygen consumption; Tlim = time limit; HR= heart rate; MAP = maximal aerobic power; * = lower than pre-training ($p < 0.05$); $^{\#}$ = higher than pre-training ($p < 0.05$).

Both the aforementioned studies reported improvement of VO_{2max}, with the Ravier et al. [100] study reporting more detailed information about the training sessions that allows the application of this training program. In the El-Ashker and Nasr [101] study the exercise intensity training was well controlled by the HR, but the method employed to predict HR_{max} (220-age equation) has some limitations as previously mentioned in the present chapter. Overall, they utilized specific movements from boxing and showed an increase of VO_{2max} as well. Kamandulis et al. [102] verified an increase in VO_{2peak} and maximal aerobic power in the experimental group composed by boxers. Finally, Monks et al. [103] verified that both the high-intensity intermittent training and the moderate-intensity continuous training increased VO_{2max} and decreased HR_{max} in the incremental test of taekwondo athletes.

As observed, there is still limited information about long-term development of aerobic fitness in combat sports. It is probably difficult to conduct well-designed studies with a good control of training program given the athletes routines. Therefore, it is noted that more studies are necessary to better understanding how the protocols may improve the aerobic fitness.

6. Means and methods to aerobic fitness development in combat sports athletes

Development of aerobic fitness involves improvement or maintaining of capacity and power of the system. To that, markers associated to these variables are evaluated as described previously. Training may be directed to improve both power and capacity because some athletes need to improve both capacities concomitantly. Considering the training principles (individuality needs, reversibility, specificity and progressive-overload), although combat sports are composed by specific movements and techniques, knowledge about the utilization of specific exercises to develop aerobic fitness in combat sports are still incipient, once all investigations used running in the training program [31,95,97,100,101,103], with exception of Borowiak et al. [94] that used running and specific movements of judo, Sterkowicz et al. [96] that used running and rowing, and Franchini et al. [98,99] that used lower- and upper-body cycle ergometer and specific movements of judo as well.

For aerobic capacity development it is recommended the utilization of moderate-intensity exercises, or intensities below the anaerobic threshold. Given that aerobic capacity is less important when compared to the development of aerobic power, the specific training to develop this ability is need only: a) when recovering from injuries, b) athletes with very low levels of this skill; and c) pre-competitive period. Nevertheless, the aerobic capacity also might be improved when training be directed to improvement of aerobic power [104]. To improve aerobic power, moderate intensity exercises are not recommended because it has little effect in aerobic power development in people who are already aerobically well-trained. The increase aerobic power and VO_{2max} of is associated with time spend with high values of oxygen consumption and it only can be reached performing high-intensity exercise [24,105]. Thus, to maintain high intensities it is necessary that the exercise be performed intermittently, because there is no way to maintain the effort in such intensities for long time.

Many variables can be manipulated during high-intensity intermittent exercise sessions, but the main variables are the intensity and effort duration, interval recovery duration and intensity, and number of efforts [24]. It is also possible to manipulate the effort-pause ratio that represents the relationship between effort duration and interval recovery duration. Consequently, when these variables are manipulated many combinations may be reached. This possibility hampers the knowledge about the effect of each one of these variables on performance but in another way allow many variations in this kind of exercise prescription.

Literature shows that the increase of VO_{2max} is positively related with exercise intensity in a range of 50 and 100% of VO_{2max} without considering the duration and training frequency [105]. Therefore, based on the premise that a greater time in intensities correspondent to VO_{2max} will result in greater benefits in aerobic power improvement some acute studies [106-109] have been conducted aiming to determine the protocols that optimize time near $VO_{2max.}$

Nowadays, a model vastly utilized to organize prescription is based on effort intensity as the main variable [24]. Thus, the intensity associated with VO_{2max} or maximal aerobic power are important markers in the development of aerobic fitness. This intensity may be determined from graded exercise test and will drive training prescription. Based in this variable it is possible to identify two kinds of protocols: high-intensity intermittent exercise (HIIE) with long and short effort durations. As mentioned above, the main characteristic of this kind of protocol is to maintain VO_2 elevated, thus all variables will be organized to achieve this goal.

Long duration HIIE are protocols performed usually between anaerobic threshold and 100% of maximal aerobic power with effort durations above 1 minute, it is common utilization of effort duration until 5 minutes [24]. Aiming maintenance of VO_2 near maximal values, recovery interval usually is performed with active pause (moderate intensity) or effort:pause 2:1.

Short duration HIIE are protocols performed usually between 100 and 120% of maximal aerobic power with effort duration lesser than 1-min, it is common utilization of effort duration between 15 and 30 seconds. As in long duration HIIE, aiming maintain VO_2 elevated, if duration effort is very short (15s), interval recovery may be passive to allow some recovery without exacerbated fatigue or use effort-pause of 2:1. But it is possible also utilization of moderate intensity active recovery in protocols with effort duration a little bit longer (30s) [110,111].

Table 33 synthesizes these protocols. All these evidences were done using running and cycling modes and there is no study with combat sports, but we can suggest that considering specific tests presented in this book it is possible to perform this kind of training based in maximal aerobic power (power or speed) determined in the specific tests.

Table 33: Examples of high-intensity intermittent exercise long- and short-duration protocols.

	Effort intensity	Effort duration	Pause intensity	Pause duration	Effort:pause
HIIE long-duration	80 to 100% of MAP	1- to 5-min	moderate intensity	30s to 5-min	1:1 or 2:1
Examples					
Buccheit et al. [112]	90% of vVO_{2max}	3-min	50% of vVO_{2max}	1.5-min	2:1
Zafeiridis et al. [113]	95% of MAS	3-min	35% of MAS	3-min	1:1
HIIE short-duration	100 to 120% of MAP	<1-min	passive or moderate intensity	15s to 1-min	1:1 or 2:1
Examples					
Dupont et al. [114]	120% of MAS	15s	passive	15s	1:1
De Aguiar et al. [115]	105% of vVO_{2max}	30s	passive	15s	2:1
Thevenet et al. [116]	105% of MAS	30s	50% of MAS	30s	2:1

MAP = maximal aerobic power; MAS = maximal aerobic speed; vVO_{2max} = velocity at maximal oxygen consumption; HIIE = high intensity intermittent exercise.

Protocols above mentioned are directed to the development of aerobic power but another way to improve this variable would be to use all-out efforts. To prescribe all-out exercises may be an interesting strategy and attractive because previous tests are not necessary to identify markers of intensity as the maximal aerobic power. We need to consider here that when we are using an all-out effort, we can increase or not the solicitation of anaerobic pathways, it will depend of the intensity that athlete will perform, but this kind of protocol allows greater approximation with temporal structure of each combat sport [117]. Thus, considering the specificity of training an interesting strategy would be the use of the effort and pause ratio observed in each modality and using specific movements from each sport. Table 34 present some examples of training to improve aerobic fitness using all-out exercise and effort and pause ratio specific for each sport.

Specifically, in the jiu-jitsu, in which the match presents long time (10 minutes) the maintenance of all out efforts may be difficult to follow. A strategy to get around this difficulty would be split the exercise using actions of high and low intensity combined with passive recovery following effort and pause ratio available in literature.

In addition, Buchheit and Laursen [24] suggested the use of anaerobic speed reserve to consider the individual characteristics for training prescription versus the prescription based in percentages of maximal sprint speed or maximal aerobic speed. The anaerobic speed reserve represents the difference between maximal sprint speed and maximal aerobic speed. In fact, this suggestion was analyzed and confirmed by Julio et al. [118] who observed that HIEE protocols based on the relative ASR (25 e 50%) compared to relative maximal aerobic speed (110%) was able to reduce the inter-subject variability of lactate (mean reduction of 48%) and time-to-exhaustion (mean reduction of 52%) in rugby players and long-distance runner.

As high-intensity interval training has been reported to improve the aerobic fitness of combat sports athletes [86], and several sport-specific tests are available to evaluate combat sports athletes [119], a combat sports specific approach using this method was proposed [85]. This approach was based on the original recommendations by Buchheit and Laursen [24] reported above, and incorporates the use of deltas between submaximal indexes and maximal aerobic power or between maximal aerobic power and maximal sprint speed. The author [85] indicated that the three parameters (i.e., a submaximal, a maximal and a supramaximal) could be determined using sport-specific tests for judo and taekwondo, whereas two of them could be identified for fencing, and taekwondo-specific test could be adapted for karate athletes. Moreover, it is likely that with the development of new combat sports-specific tests, improved training prescriptions to enhance aerobic fitness will be possible in the near future.

Table 34: Model of training prescription to maintain or improve aerobic fitness based in effort and pause ratio of each modality (E:P).

Modality	N° and duration of round	Movement	N° of blocks x efforts	Duration and ratio E:P	Interval between blocks
Judo					
International, state and local	1 x 5-min	Technique entrance (*uchi-komi*, all out) moving	2 x 10	18:12s 2:1	5-min
		Technique entrance projecting (*nage-komi*, all out) moving	2 x 10	30:11s 3:1	10-min
Jiu-Jitsu					
Local	1 x 10-min (black belt)	Sequence of drills (all out, pauses of 5s between the passages in 2 or 3 partners)	3 x 5	117:33s 3.5:1	10-min
International			3 x 5	170:13s 13:1	
Wrestling					
International	2 x 3-min (30s between rounds)	Fencing (5s) technical entrance raising partner (all out), alternate partner each set	3 x 4	37:14s 2.6:1	1-min
Taekwondo					
State	3 x 2-min (1-min between rounds)	Alternate kicks (all out) in punching bag; stepping in recovery intervals	3 x 15	8:8s 1:1	2-min
International*				2:13s 1:6	
Boxing					
National	3 x 3-min (1-min between rounds)	Alternate punches (all out) in punching bag; dodges in recovery intervals	3 x 30	64:7s 9:1	1-min
Muay-Thai					
Amateurs	3 x 3-min (1-min between rounds)	Alternate punches and kicks (all out) in punching bag; dodges in recovery intervals	3 x 20	9:13s 1:1.5	3-min
Karate					
National	1 x 3-min	Alternate punches and kicks (all out) pad-work; dodges and feints in recovery interval	3 x 12	10:16s 1:1.5	1-min

*= time-motion analysis was performed considering time with technique application divided by time without technique application.

7. Final considerations

Based in the current literature it is possible to conclude that there is high aerobic solicitation in combat sports. This solicitation occurs since the first moments of the match with a time-dependent increase, *i.e.*, the oxidative contribution increases according to the match duration. Nowadays, for all combat sports aforementioned, HR values in match situation are already known, while for VO_2 only for jiu-jitsu and wrestling this type information is not available. Considering specific exercises, information about HR and VO_2 is scarcer because only for judo, karate, taekwondo and boxing information about HR and VO_2 values are known. Knowledge about the effect of different long-term training programs aiming develop aerobic fitness is still incipient, being that this type of investigation began in 2009. Finally, methods to evaluate combat sports athletes also need refinement because there are only aerobic fitness specific tests to evaluate judo, karate and taekwondo athletes.

Conflict of interest

None declare.

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