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Special Issue

Strength and Conditioning for Combat Sports Athletes

Edited by
Emerson Franchini and
Tomás Herrera-Valenzuela

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Presentation of the Special Issue

Strength and conditioning for combat sports athletes

Carlos GUTIÉRREZ-GARCÍA*

Universidad de León (Spain)

Editor-in-Chief of the Revista de Artes Marciales Asiáticas

The *Revista de Artes Marciales Asiáticas* was launched in 2006 with lots of passion and the clear aim of "spreading of studies on martial arts and combat sports, enabling a better understanding of their diverse manifestations", as it is stated in our website. Since then, we have done our best to fulfil this objective. Several milestones could be cited in this regard. In the same year of 2006, we published the first original paper of, by that time, Spanish version of the *Journal of Asian Martial Arts*. Six years later, in 2012, RAMA turned from a print to an on-line, open-access journal, and reinforced its current academic approach. No doubt, this made RAMA a truly international journal. Our first special issue was published in 2016, being the book of abstracts of the *5th IMACSSS World Scientific Congress* (Rio Maior, Portugal, October 6-8). By starting publishing special issues, we did not want to miss the opportunity to spread contributions to martial arts and combat sports (MA&CS) knowledge presented in scientific events that, many times, are soon consigned to oblivion. Thanks to scientometrics, we know that some of these contributions are having impact in the MA&CS scientific community.

I feel this special issue marks a new milestone in the still short history of RAMA. It presents a full book, which may be seen as unorthodox, but coherent, approach with respect to the journal purpose. Once again, and regardless of format, we have seen a clear opportunity to provide the MA&CS scientific community with a valuable piece, in this case on MA&CS physical training. Let me tell you a bit about how this book has become published in RAMA.

Some months ago, our colleague and RAMA Editorial Board member Prof. Emerson Franchini told me that he, along with Prof. Tomás Herrera-

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Valenzuela, were preparing the English version of their book *Strength and conditioning for combat sports athletes*, which had been previously published in Portuguese, Spanish and Italian, as Profs. Franchini and Herrera-Valenzuela explain in the following preface. I knew about this book since it was published in Portuguese in 2016, and was happy that an English version could be soon available. When I asked Prof. Franchini about which publishing house would print the book, he told me they were considered several possibilities. – "Well", I said, "maybe you could think of RAMA. We cannot provide you for any payment, but if you want for the book potentially reach everyone interested in MA&CS physical training, RAMA is certainly a good means."

The proposal was accepted, which gives an idea of Profs. Franchini and Herrera-Valenzuela generosity. Immediately we started to work. The authors had updated the book contents. Every chapter was then anonymously reviewed by two or three of our reviewers. This was a key process to ensure the quality of the book contents, following the regular journal reviewing processes. I would like to express my deepest gratitude to this committed group of experts who, from the very beginning, understood the dimension and relevance of the project and selflessly accepted to collaborate. Also, to the authors, who attended to the reviewers' suggestions in detail and carefully reviewed the successive versions of their chapter until it was accepted. And, finally, to Prof. João Paulo Lopes-Silva, who has been the key person during all the reviewing and editing process.

Strength and conditioning for combat sports athletes is an outstanding piece. It provides a scientific, comprehensive and up-to-date approach to MA&CS physical training. The authors synthetize the knowledge of hundreds of documents to present a brilliant handbook, which should serve to train MA&CS athletes with effective, safe and well-founded methods. For many years, it has been said that sport research should be close to sport practice and vice-versa. This book approaches these two worlds. We hope you, MA&CS trainer, athlete, scientist or student, will enjoy it.

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Preface

Strength and conditioning for combat sports athletes

Emerson FRANCHINI*[1] & Tomás HERRERA-VALENZUELA[2]

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Combat sports have grown in popularity worldwide and in increased number of events, resulting in more athletes taking part in competitions of different levels. Along with this growth, there is a need to develop safer and more scientifically oriented training methods. As performance in combat sports depends on the combination of different physical attributes, it is important to know in detail the relevance of each of these aspects to competitive success. From this knowledge, training means can be better designed to meet the sport-specific needs as well as athletes' characteristics and physical fitness.

The specialized literature presents numerous investigations on the training of different physical abilities of combat sports athletes, however, this material is not often accessible to professionals working in this segment. Additionally, there are no book synthesizing the different aspects to provide a detailed understanding of the physiological responses to competition and training sessions for combat sports athletes or to elaborate the training process to develop each of these variables. Thus, this book is an initiative aimed at detailing the physiological and physical performance under different conditions of combat sports practices, presenting studies that have investigated the training process to allow the training prescription using an evidence-based approach.

The history of this book began in 2014, when a group of passionate young researchers accepted the challenge of searching the available literature about physiology, physical training and combat sports, and selecting the most relevant findings to be presented not only to other researchers, but to professionals working directly with combat sports athletes. At that time most of the authors were completing their PhD studies. The first version of this book was published in 2016, in two volumes, only in Portuguese. Fortunately, this book found good hands abroad and in 2017 it was published in Spanish thanks to the efforts of Dr. Tomás Herrera-Valenzuela, who came on board to stay, and to the Editorial Kinesis, which believed that this book deserved to be read by the Spanish speakers.

In the same year, the Spanish version found Dr. Roberto Manno, a great Italian researcher, the coordinator of the scientific commission of the Federazione Italiana de Judo Lotta Karate Arti Marziali (FIJLKAM). This book was then presented to the President of the FIJLKAM, who gave its support to an Italian version. A new translation, a new publisher (Calzetti & Mariucci) and more people could have access to the book content in 2019.

The time goes fast. Most of the authors now hold their PhDs and have their positions in different universities across Brazil. However, their passion for combat sports, sport sciences and its applications made possible a revised and extended version of the original book. Despite their busy schedules, each author contributed with his/her knowledge, experience and enthusiasm to a new version. Once again, we were lucky to find a group of dedicated people to collaborate in this process.

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Carlos Gutiérrez García, Editor-in-Chief of *Revista de Artes Marciales Asiáticas*, and his team of reviewers helped us to improve the book content. Our deepest thanks to him for putting a great group of experts together, and to the, at that time, anonymous reviewers for their precise and valuable suggestions and comments. Now it is time to a broader number of readers, as the book is available in English. In great part this English version was possible because one of the authors, João Paulo Lopes-Silva, organized the whole translation process, motivating all the contributing authors, from whom he received full support and cooperation. A true team work. We think we speak on behalf of all the authors when we say: *Thank you very much João!!!*

We hope the reader will find relevant information to improve the training prescription of their athletes.

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Foreword

Strength and conditioning for combat sports athletes

Leandro Marques GUILHEIRO

Double Olympic judo medallist (bronze in Athens-2004 and Beijing-2008, -73kg)
Double Judo World Championship medallist (silver in Tokyo 2010 and bronze in Paris 2011, -81 kg)

"I was told by Inokuma-sensei to foster a scientific eye toward judo". These words of Nobuyuki Sato in his book *Best Judo* describe the approach applied by him, together with Isao Inokuma, in the newly created Martial Arts Department, focusing on judo, in the victorious Tokai University, in the 1960 decade.

Beyond their brilliant careers as athletes (Inokuma was Olympic champion in 1964 and World champion in 1965, whereas Sato was twice World champion, in 1967 and 1973), both were the mentors of that who is considered the most successful judo athlete of all time, Yasuhiro Yamashita. Olympic champion in 1984, World champion in 1979, 1981 (in the heavyweight and open categories) and 1983, Yamashita inherited not only part of his teachers' technical prowess, but also the scientific view of sport, giving to physical preparation the due importance it deserves. It is not by chance that in his book *The Fighting Spirit of Judo* Yamashita exposes his physical training routine and emphasizes the need to study more current methods to improve performance in this aspect.

It is likely that the fact that the main Japanese judo teams belong to the universities makes this symbiosis between the academy and the dojo a natural process. This union seems obvious, given that all information available to improve performance, decrease injury rate and optimize the time of coaches and athletes must be absorbed by those working with high-level sports. It can be said that this approach is an application of the *Seiryoku-Zenyo*, a judo principle that preconizes the most efficient use of physical and mental energy.

My first contact with physical training involving strength training, in weight training room, was in 1999, when I was 16 years-old. At that time, I trained with a former judo athlete and physical education professional, Marcus Daud. In that period, I started to realize that my body was more prepared to the high-volume of training I was submitted daily. In 2006 I changed of judo team and started to train under Professor Emerson Franchini supervision, who had a different approach to organize my training. Under his direction, the number of my weekly physical training sessions doubled and the type of exercises and stimuli had a characteristic I have never experienced up to that moment. Although I was a complete white belt concerning the execution of Olympic weightlifting and other complex exercises, the effort to learn them proved valuable.

Besides I never suffered any kind of muscle injury again, I started to feel safer when having closer contact with my opponents, since my legs guaranteed me a better and stronger base; my arms and hands got stronger, increasing further the pressure I could exert on my opponents' *judogi*; my techniques became more powerful, making me win more matches by *ippon*, and as my body was even stronger I was able to save energy and maintain a high rate of attacks during the match for a longer time. Therefore, a well-planned physical training was determinant for the evolution of my judo, including in the technical and tactical aspects.

But my evolution was not just concerning my body. The proximity to Professor Franchini made me see judo from another point of view. I started to be more critical, I began to undress pre-conceived biases and tried to stick to observable facts. I can say that I was taken by the "scientific look in relation to judo" and the results of this approach will be recorded forever in my history as an athlete.

All combat sport athletes need to be strong, powerful, flexible and to have stamina. The next pages of this book will serve as a rigorous guide for those who wish to work and develop these physical capacities in an athlete. Take advantage of this privilege!

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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

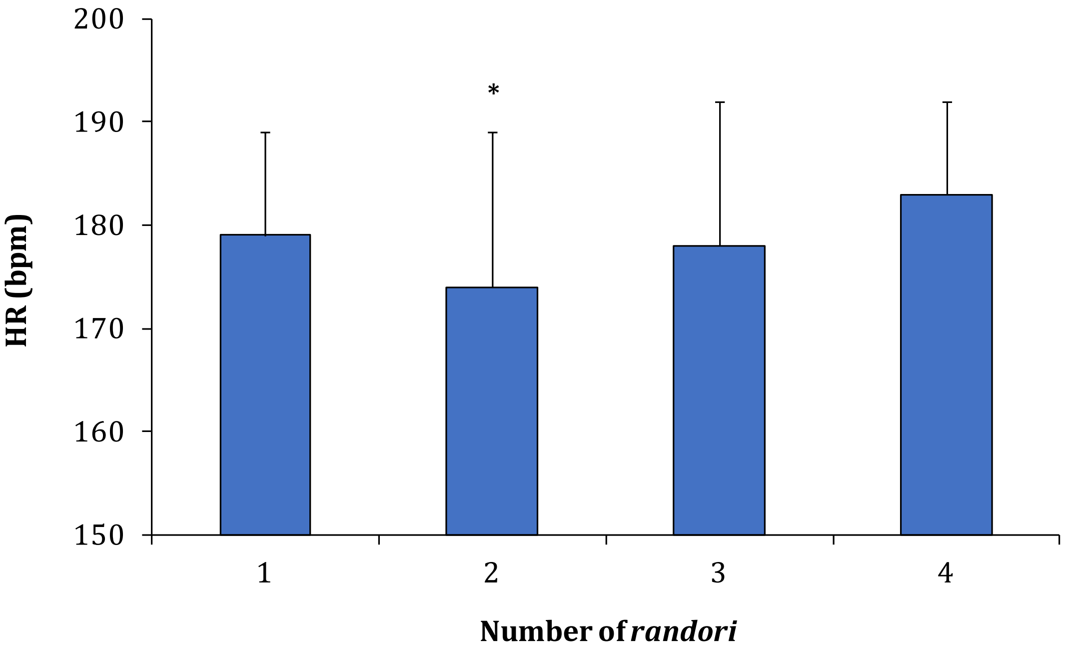
Kaneko, Iwata, and Tomioka [22] analyzed the VO_2 of five judo athletes in two different training situations, including *randori* (a match conducted during the training sessions on a continuous basis and without the intervention of a referee to apply the rules, mainly to establish pause periods). In 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).



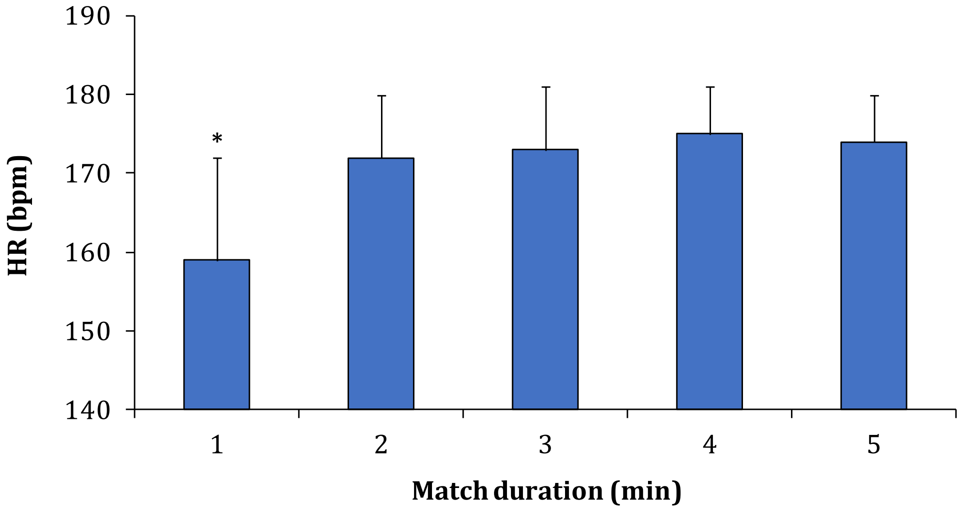
* = different from third *randori* ($p < 0.05$).

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.



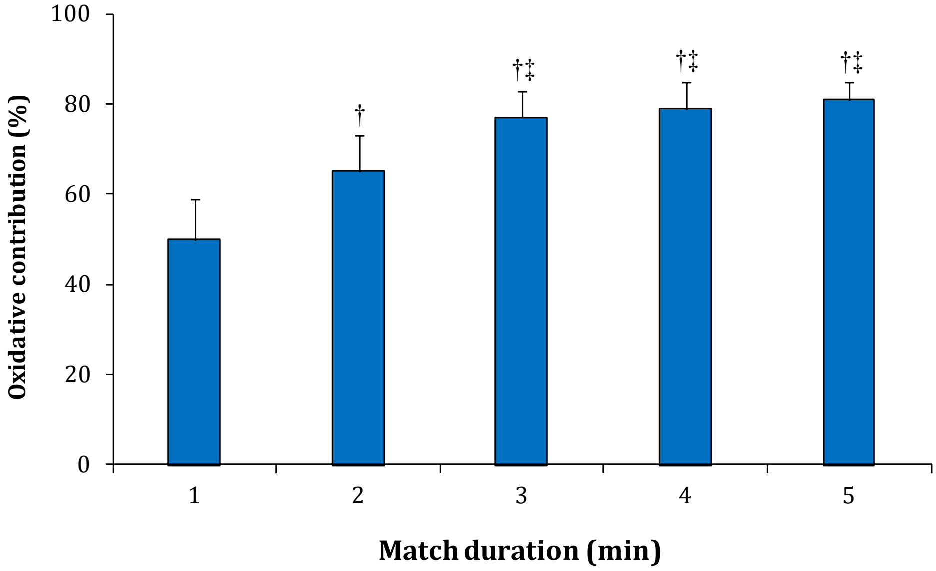
* = different from longer matches duration ($p < 0.05$).

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.

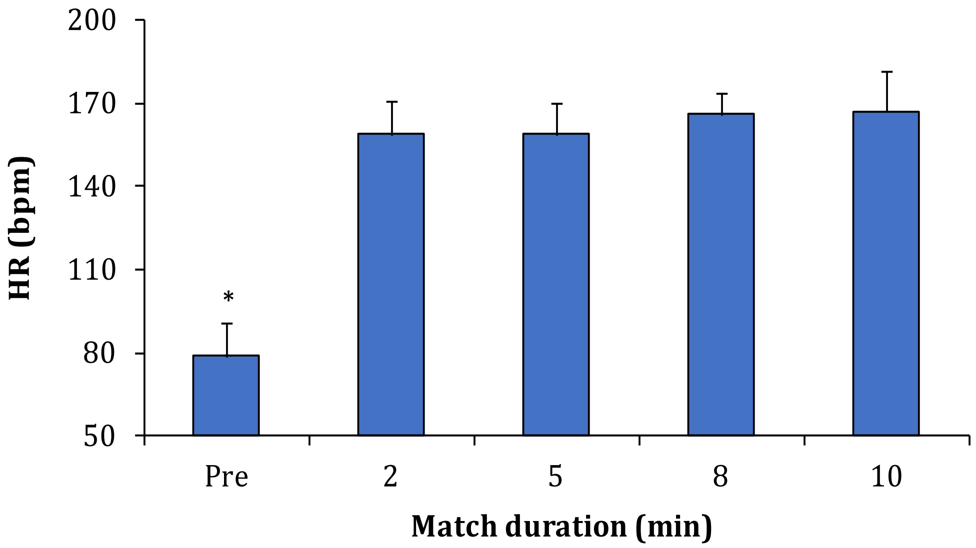
2.1.2. Jiu-Jitsu

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.

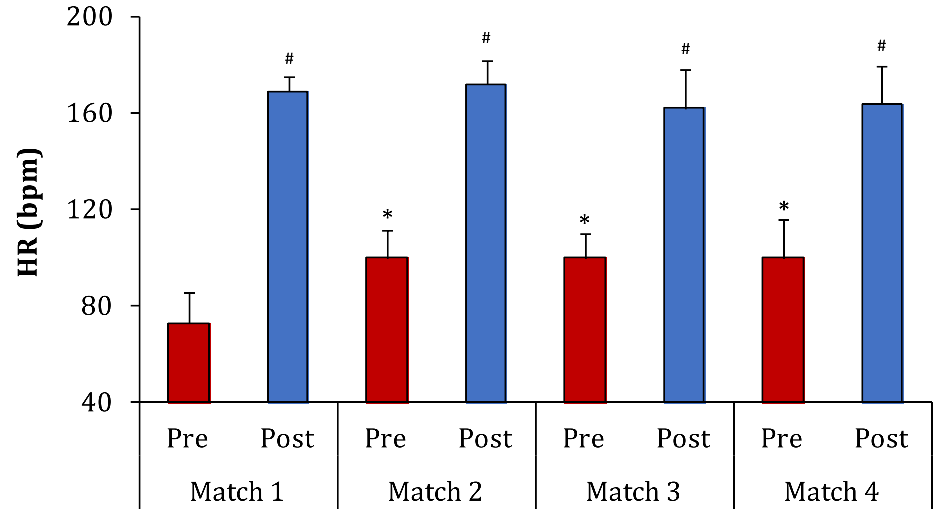
Two studies were performed to understand HR time course during the match [39] and during simulated competition (four matches in the same day) [40]. In Andreato et al. [39], 10 jiu-jitsu athletes, brown and black belt, were submitted to four matches with different match durations (2, 5, 8 and 10-min), 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.

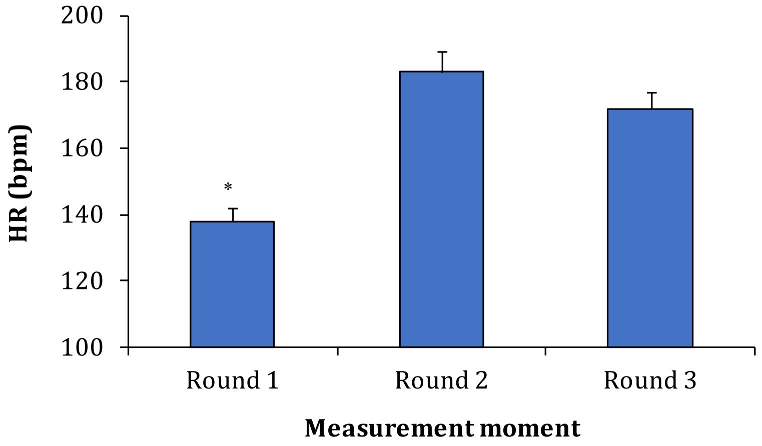


Figure 6: Heart rate response in different time of measurements during simulated Greco-Roman wrestling match composed of three 2-min rounds (Adapted from Theophilos et al. [43]).

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

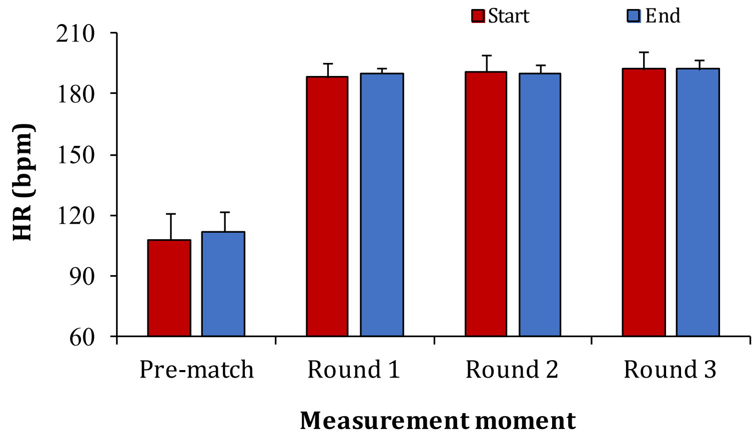
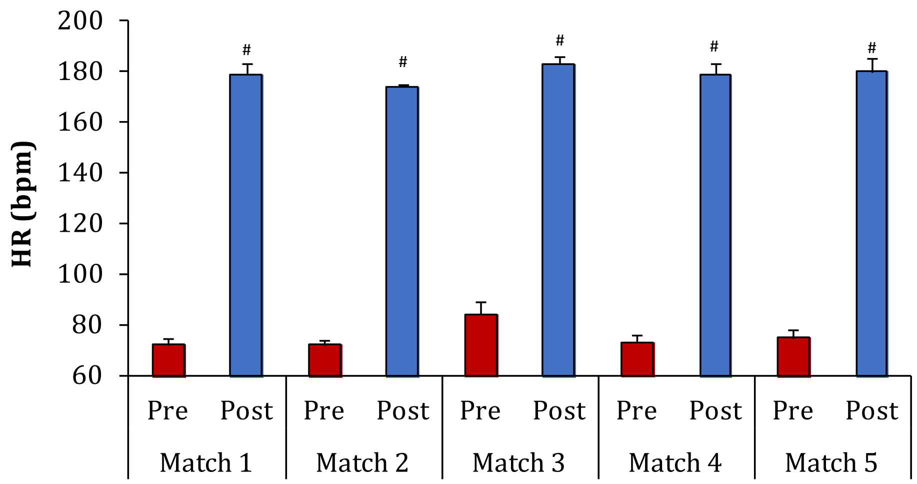


Figure 7: Heart rate response in different times of measurements during simulated Greco-Roman wrestling match composed by three 2-min rounds interspersed by 30s interval, in the beginning and at the end of a competitive period (Adapted from Karninčić, Baić and Sertić [42]).

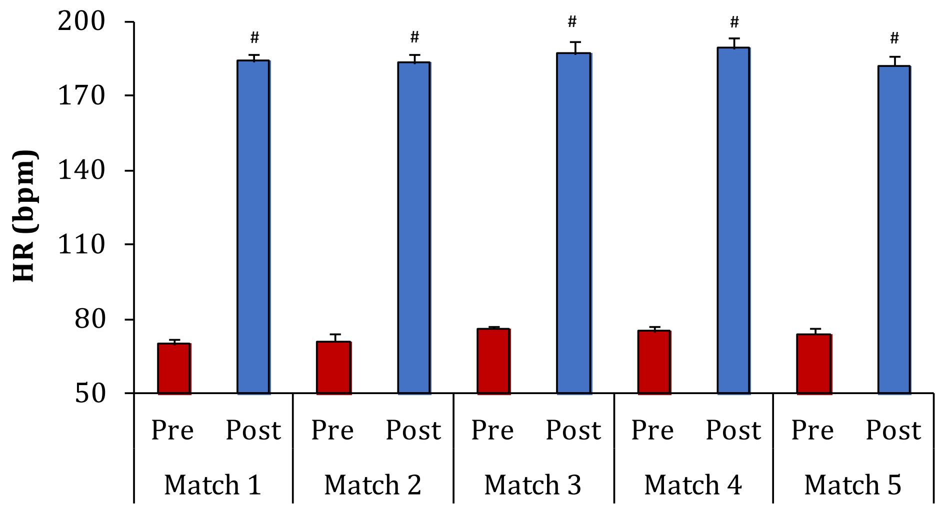
Kraemer et al. [44] submitted 12 freestyle wrestlers to a simulated competition over two days (simulating competition at that period). Athletes were submitted to a 6% body mass reduction in a week (range between 4.6 and 6.8%), being allowed a 2% tolerance in the second day of competition. On the first 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.

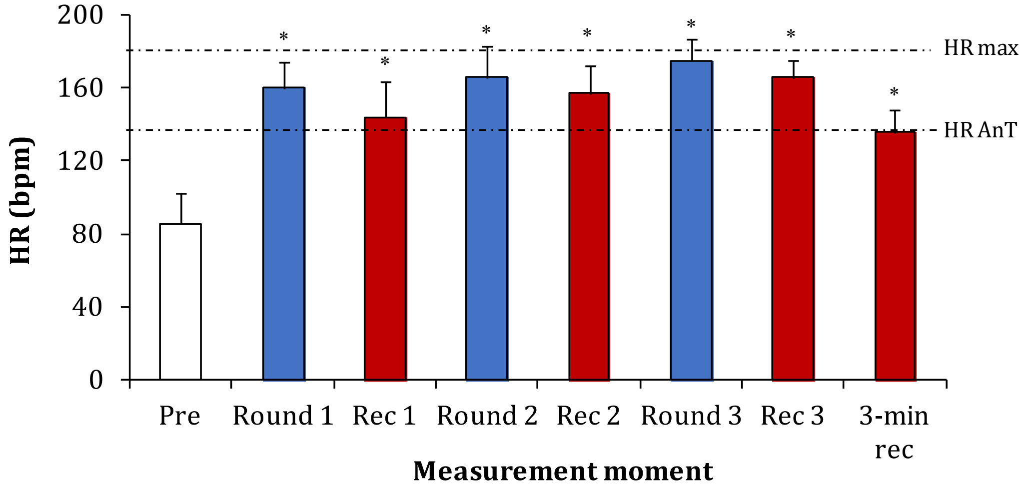
	HR	**VO2**
Are there studies describing these variables?	Yes	No
Are there mean values during the match?	Yes	NS
Are there post-match values?	Yes	NS
In a single match, is there an increase in pre-match values?	Yes	NS
In a single match, but fragmenting the total duration of match, is there an increase in 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

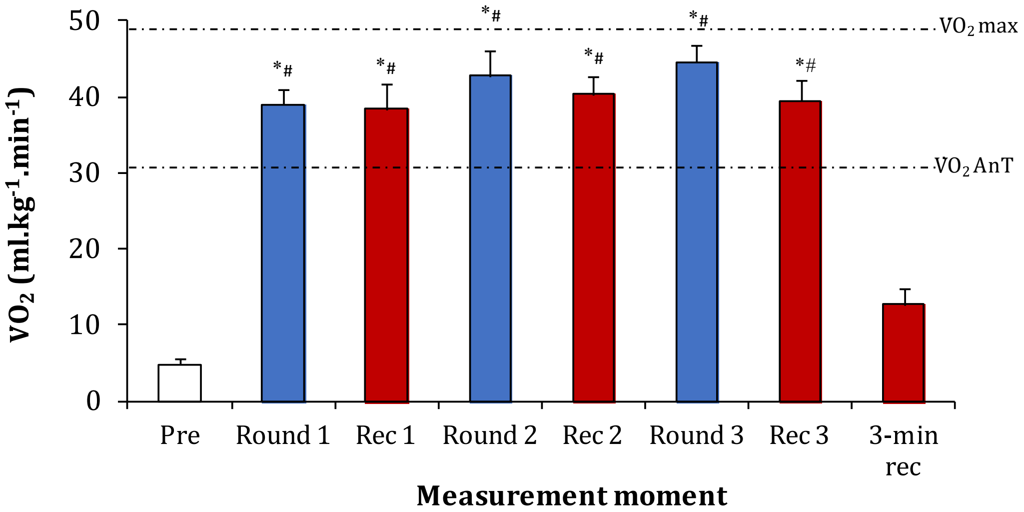
2.2.1 Muay-Thai

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 ($p < 0.05$).

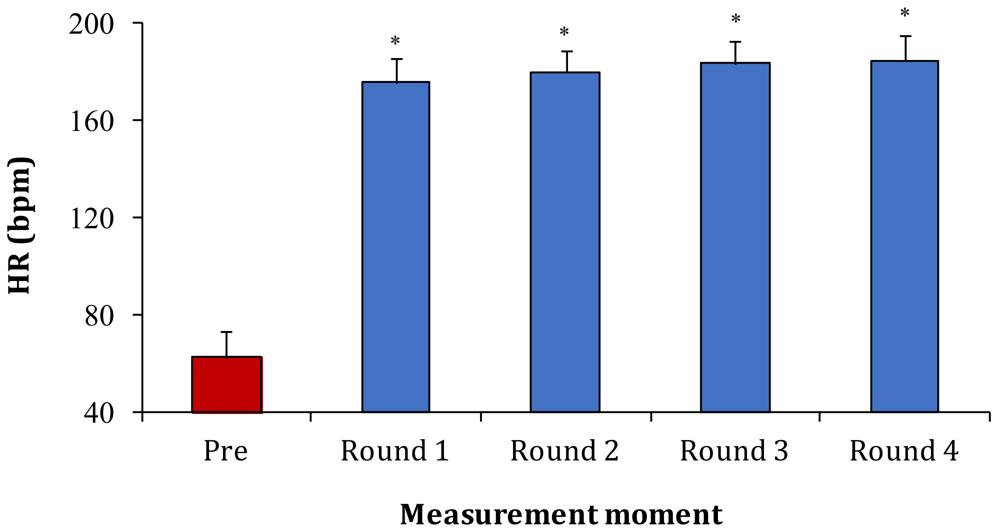
Figure 10: Heart rate response during different time points of a muay-thai simulated match (three 2-min rounds interspersed by 30s interval) and after 3-min recovery (Adapted from Crisafulli et al. [6]).



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.).

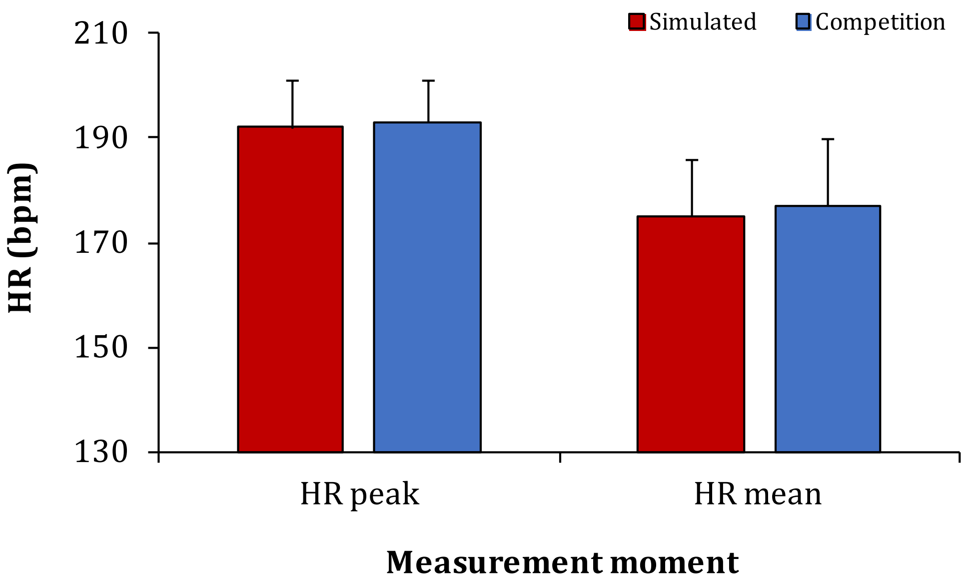


Figure 13: Peak and mean heart rate response in simulated and competitive karate matches (Adapted from Chaabéne et al. [48]).

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

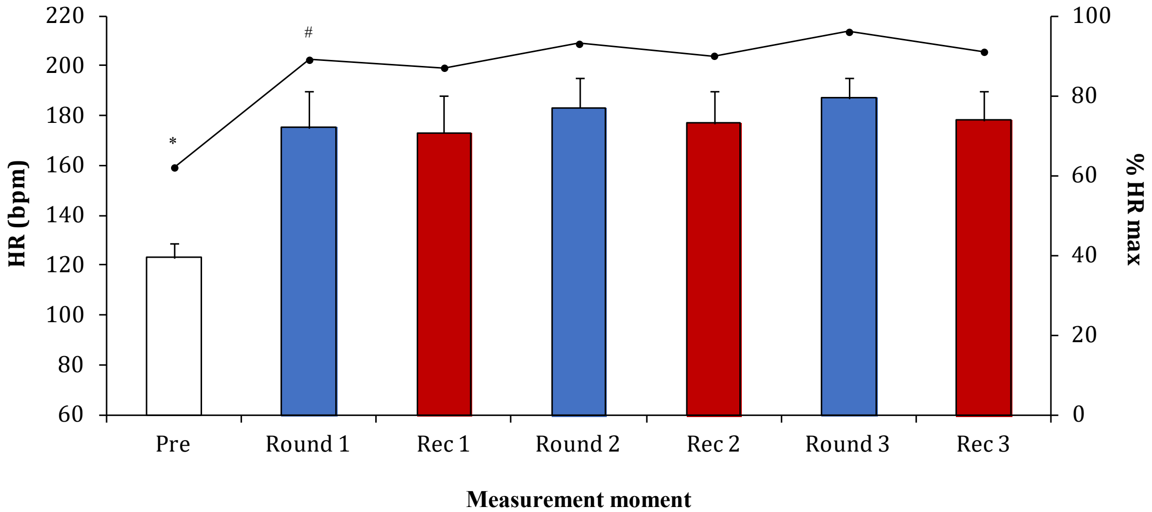
	HR	**VO_2**
Are there studies describing these variables?	Yes	Yes
Are there mean values during the match?	Yes	Yes
Are there post-match values?	Yes	NS
In a single match, is there an increase in pre-match values?	Yes	Yes
In a single match, but fragmenting the total duration of match, is there an increase 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.

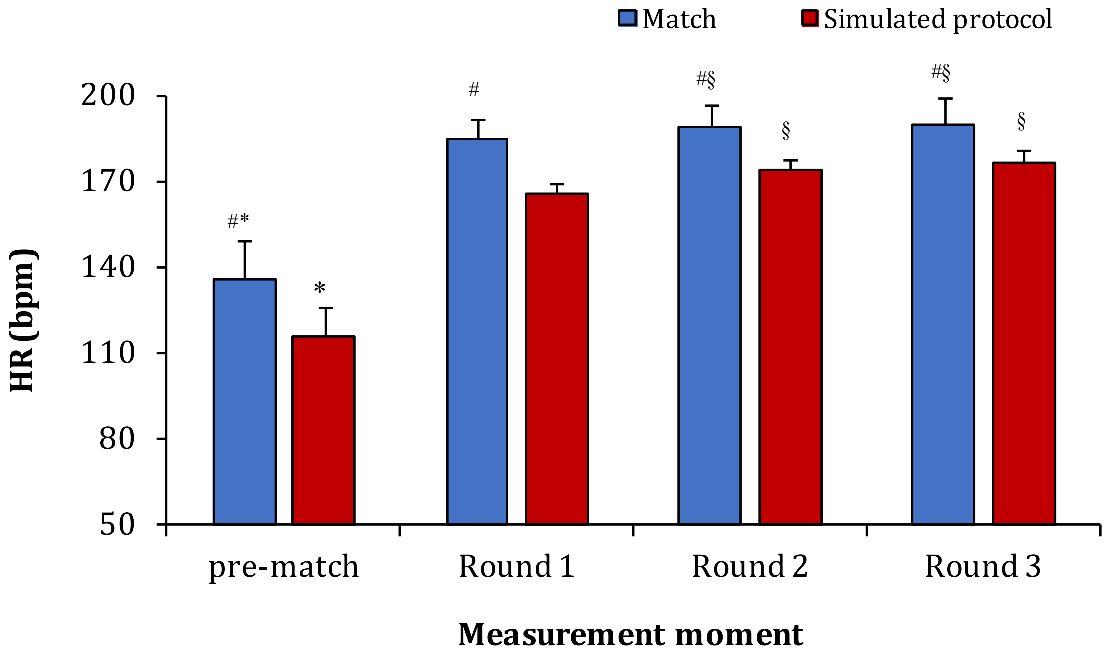


rec = recovery; * = different from rounds 1, 2 and 3 ($p < 0.05$); # = different from round 3 ($p < 0.05$).

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).

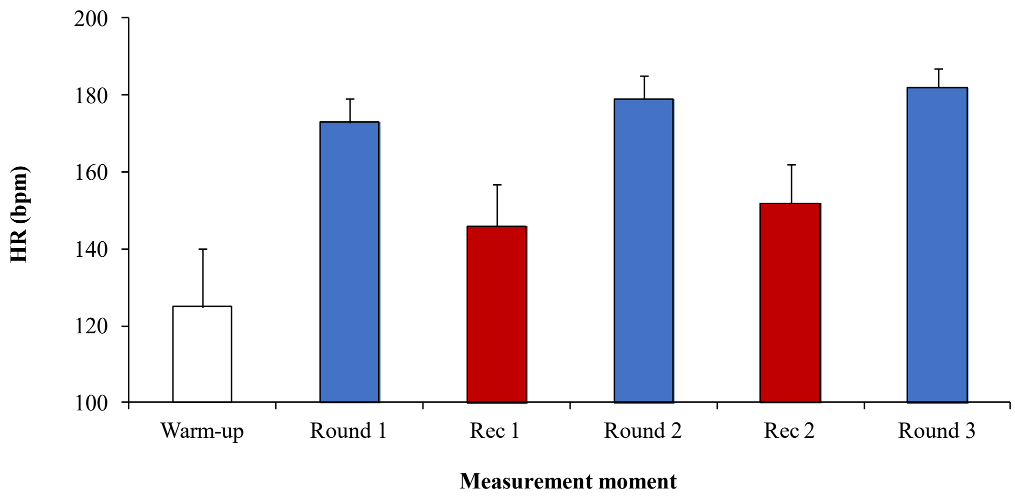
Table 7: Findings available in the literature on heart rate (HR) and oxygen uptake (VO_2) in taekwondo.

	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.

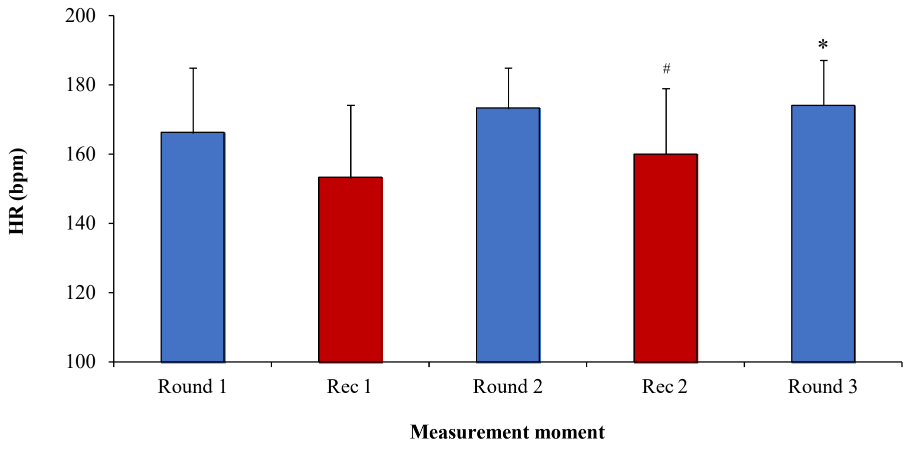


Figure 17: Heart rate response in different times of measurement in a boxing match composed by three 2-min rounds interspersed by 1-min recovery (Adapted from Davis et al. [56]).

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

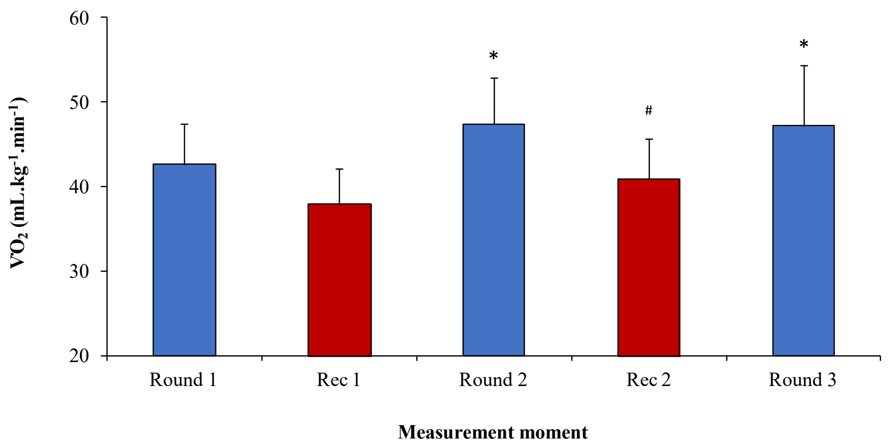


Figure 18: Oxygen consumption response in different times of measurements in a boxing match composed by three 2-min rounds interspersed by 1-min recovery (Adapted from Davis et al. [56]).

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

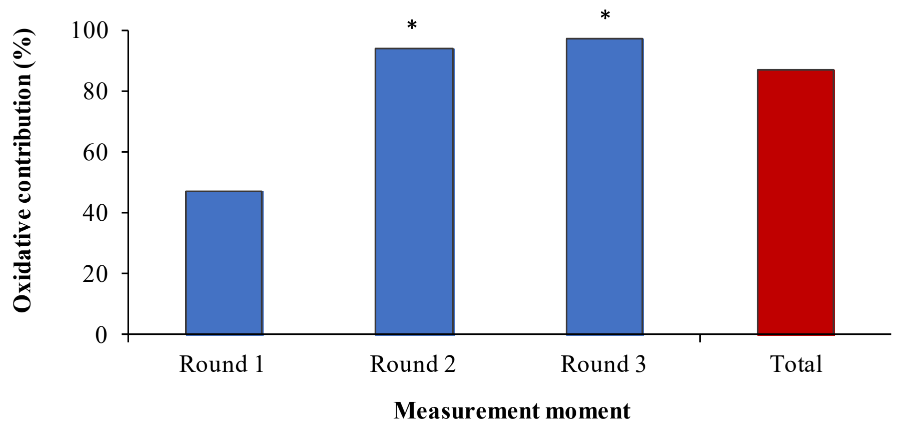


Figure 19: Relative oxidative system contribution in different times of measurements in a boxing match composed by three 2-min rounds interspersed by 1-min recovery (Adapted from Davis et al. [56]).

* = 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? At what point does this increase occur? Is there a progressive increase in these values?	Yes 1st round Yes	Yes 1st round 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.

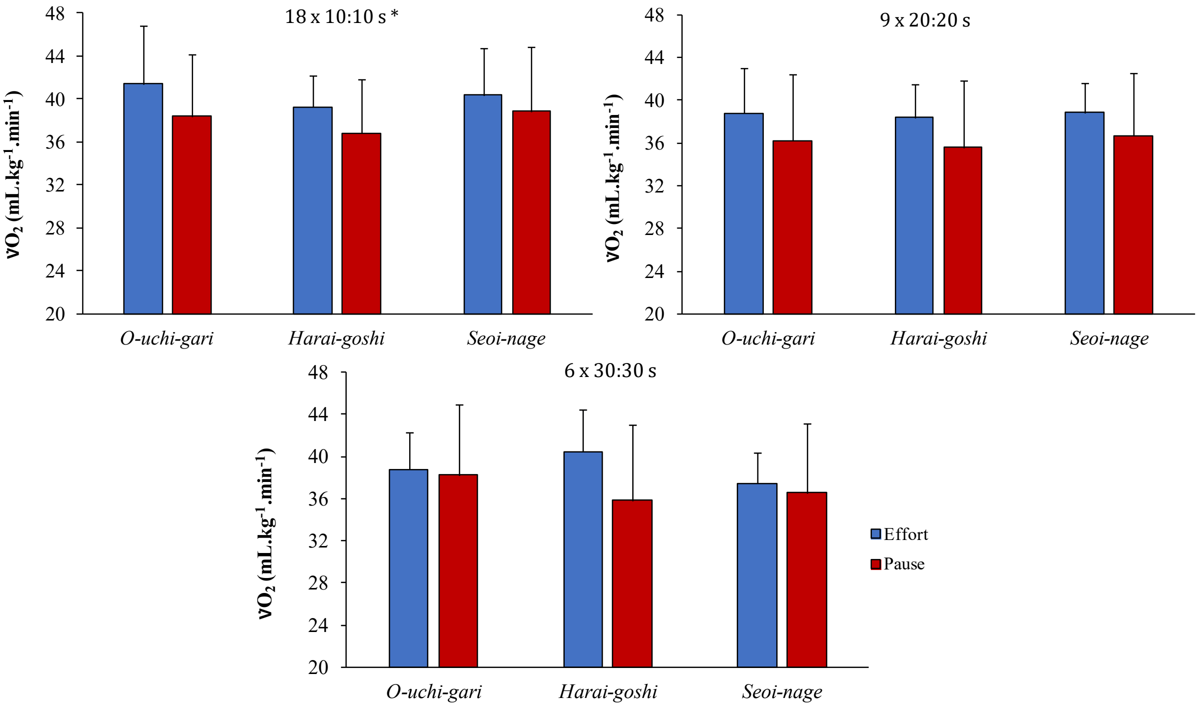
3.1. Grappling combat sports

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]).

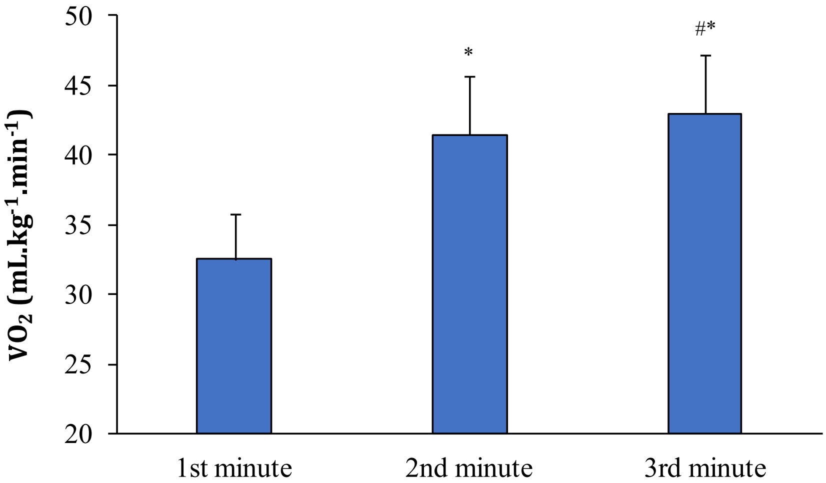


Figure 21: Oxygen consumption values during a 3-min effort during all-out *uchi-komi* sessions using different techniques and time structures (Adapted from Franchini, Panissa and Julio [11]).

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

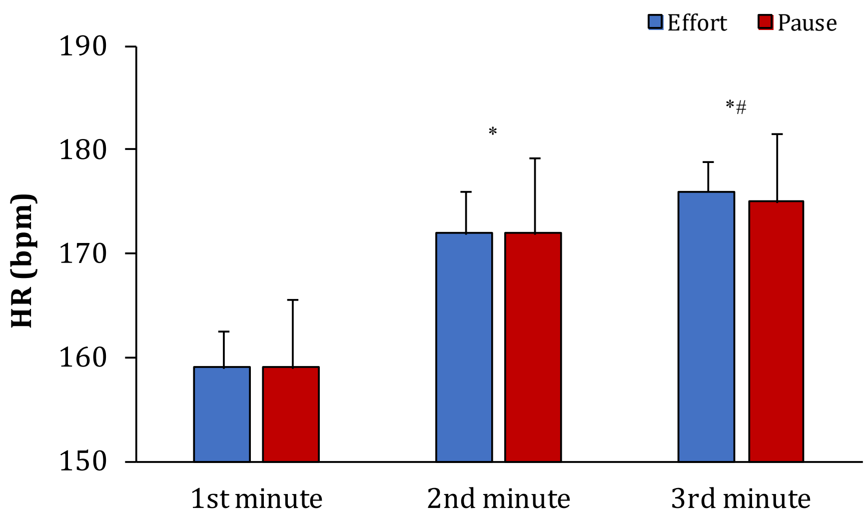


Figure 22: Heart rate values during a 3-min effort and pause during all-out *uchi-komi* sessions using different techniques and time structures (Adapted from Franchini, Panissa and Julio [11]).

* = 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]).

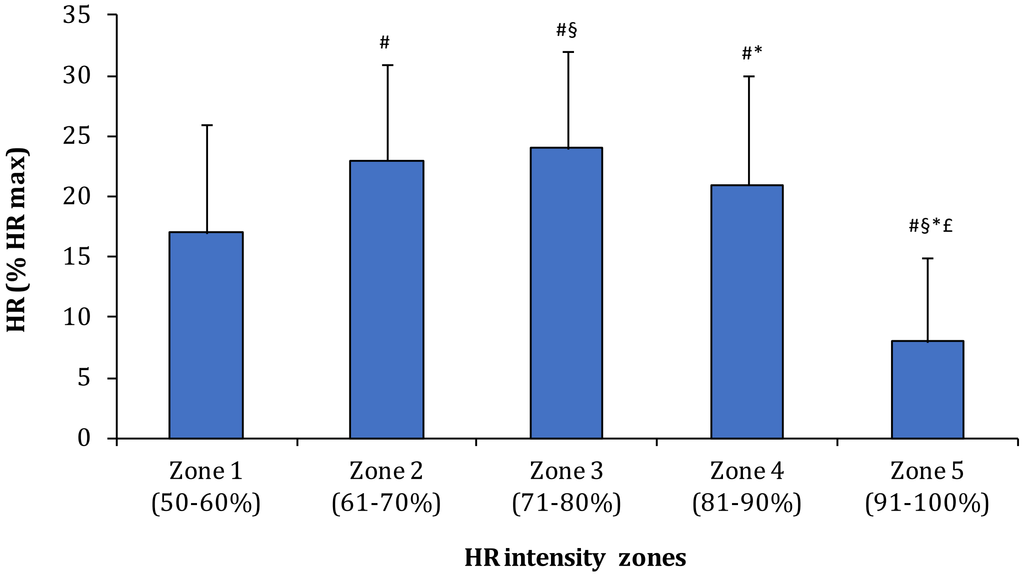
	HR (bpm)	HR ($\%HR_{max}$)	HR ($\%HR_{res}$)	VO_2 ($ml·kg^{-1}·min^{-1}$)	VO_2 ($\%VO_{2res}$)
S-basics	100 ± 10	23 ± 5	35 ± 5	9.4 ± 0.9	20 ± 2
M-basics	145 ± 15	43 ± 8	65 ± 8	20.8 ± 2.8	47 ± 5
TECH1	145 ± 20	43 ± 8	63 ± 10	17.0± 1.9	38 ± 5
TECH2	140 ± 10	40 ±5	63 ± 5	15.0 ± 0.9	32 ± 2

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.

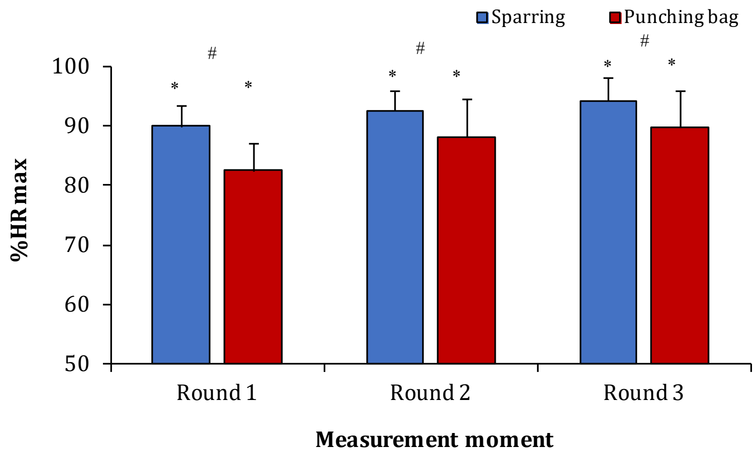


Figure 24: Percent of maximal heart rate response in two boxing activities during three rounds (Adapted from Arsenau, Mekary and Léger [73]).

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

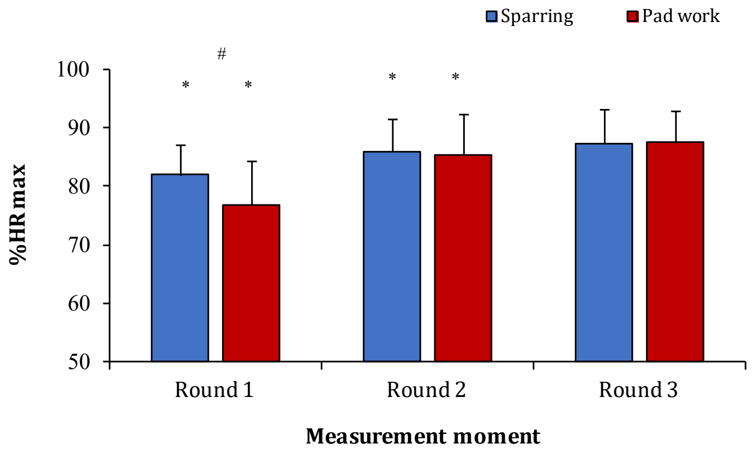
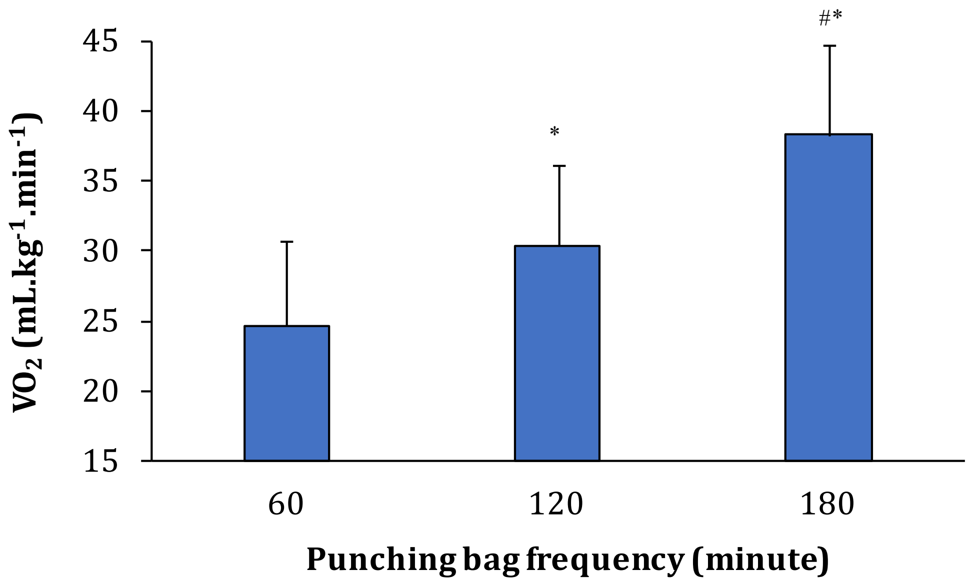


Figure 25: Percent of maximal heart rate response in two activities (sparring and pad work) in three rounds (Adapted from Arsenau, Mekary and Léger [73]).

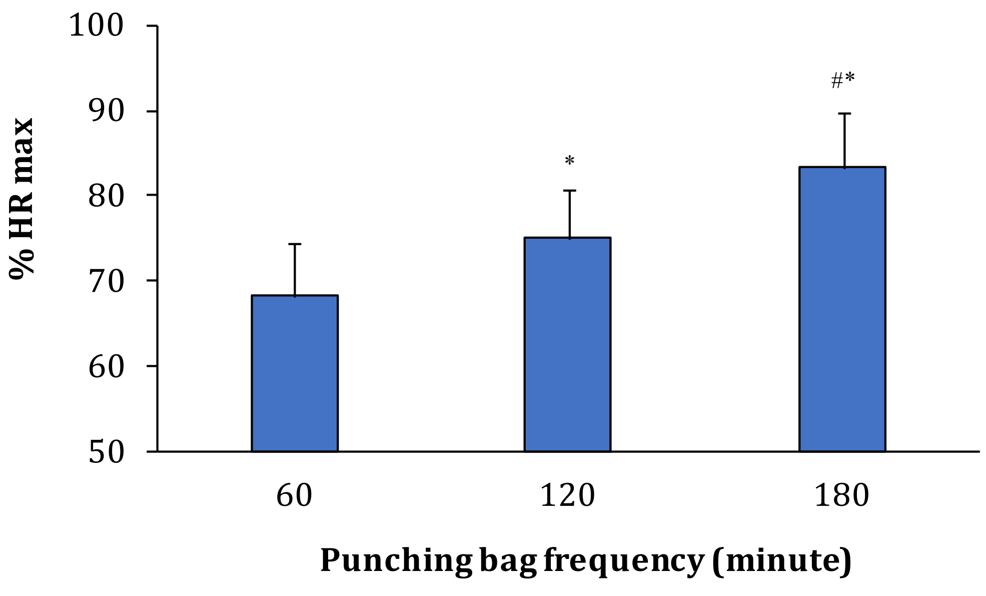
$\%HR_{max}$ = percent of maximal heart rate; # = different from *sparring* ($p < 0.05$); * = different from round 2 ($p < 0.05$).

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):

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

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 ($rep \cdot min^{-1}$)	57 ± 3	58 ± 4	0.12
Peak oxygen consumption ($mL \cdot kg^{-1} \cdot min^{-1}$)	46.04 ± 5.34	46.55 ± 4.91	0.57
Maximal heart rate (bpm)	183 ± 5	184 ± 7	0.19
Peak blood lactate ($mmol \cdot L^{-1}$)	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} ($mL \cdot kg^{-1} \cdot min^{-1}$)	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 ($mmol \cdot L^{-1}$)	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 ($mL \cdot kg^{-1} \cdot min^{-1}$)	0.78	.003	0.87	<.001
Maximal heart rate (bpm)	0.50	.139	0.68	.035
Peak blood lactate ($mmol \cdot L^{-1}$)	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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CHAPTER 2
Developing anaerobic power and capacity for combat sports athletes

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Abstract
This chapter describes the physiological responses associated with anaerobic power and capacity of combat sports athletes from different modalities (judo, Brazilian jiu-jitsu, wrestling, Olympic boxing, karate, and Muay Thai) during specific situations. Next, the most used evaluation methods for the control and monitoring of these variables are presented. Finally, based on longitudinal studies that evaluated the effects of anaerobic power and capacity training of combat sports athletes, the main training approaches are presented.

Keywords: Martial arts; combat sports; physical fitness; HIIT; high-intensity intermittent exercise.

1. Introduction

Combat sports are classified as intermittent activities, during which there are periods of high-intensity interspersed with short periods of recovery and it can be observed in diverse modalities such as judo [1], Brazilian jiu-jitsu [2], wrestling [3], taekwondo [4], karate [5] and Olympic boxing [6]. For example, combat sports as judo, Brazilian jiu-jitsu, and wrestling effort-pause ratio is between 2:1 or 3:1 [3,7-9], while in taekwondo, karate the interval periods are longer, with an effort-pause ratio of 1:6 to 1:9 [10-12]. Furthermore, mixed martial arts (MMA) shows an intermediate effort-pause, between 1:2 and 1:3 [13]. Thus, the development of training strategies and methods of assessing athlete's physical performance should be based on the request of different energy systems, which are difficult to quantify but can be inferred when considering each modality effort-pause ratio.

During physical activity, the immediate source of energy for muscle contraction comes from the hydrolysis of Adenosine Triphosphate (ATP) that is dependent on the duration and intensity of exercise [14]. The anaerobic energy system is divided into alactic and lactic components, referring to the processes involved in the splitting of the stored phosphagens, ATP and phosphocreatine (PCr), and the nonaerobic breakdown of carbohydrate to lactic through anaerobic glycolysis. The aerobic energy system refers to the combustion of carbohydrates and fats in the presence of oxygen [14]. During a combat, oxidative metabolism is the main metabolic pathway to provide energy during the rest period between high-intensity actions – especially during referee interruptions, while the ability to maintain high-intensity actions is derived from PCr system and the anaerobic lactic system is activated during repetitive periods of high-intensity activities (grappling) [1,15].

Anaerobic fitness is subdivided into capacity and power, which are performance's determinants during intermittent activities, such as combat sports. Anaerobic capacity is defined as the total energy that can be transferred by anaerobic metabolism[16], while anaerobic power is defined as the maximal amount of energy that can be generated per unit of time [17]. In this sense, the use of methods capable of evaluating the capacity and power anaerobic of fighters is an important factor, considering the development of these variables during training sessions.

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Although there is no gold standard method for assessing anaerobic capacity [18], the most utilized methods are total work performed in standardized tests, as Wingate test, maximal of accumulated oxygen deficit (MAOD) [14] as well as some physiological responses to standardized tests or in specific situations, such as lactate concentration. On the other hand, the evaluation of the anaerobic power occurs through mechanical variables, for example, peak power during the Wingate test [17].

Thus, this chapter describes the physiological responses associated with the anaerobic capacity and power of fighters (judo, Brazilian jiu-jitsu, wrestling, Olympic boxing, karate, and Muay Thai) during specific situations. After that, the most commonly used evaluation methods for the control and monitoring of these variables are presented. Finally, based on longitudinal studies that evaluated the effects of strategy training based on anaerobic capacity and power of fighters, will be presented training strategies with the objective of developing these capacities.

2. Anaerobic responses in combat sports

2.1 Lactate concentration during combat simulation

Lactate concentration is utilized to estimate to assess anaerobic glycolytic energy contribution during exercise. Thus, lactate concentration will be categorized as low < 3 mmol·L^{-1}, moderate > 6 mmol·L^{-1}, high >10 mmol·L^{-1} and very high >14 mmol·L^{-1} [19]. Thus, several studies have analyzed the lactate concentration during a combat simulation in karate athletes [10,20-22], taekwondo [23-26], Muay Thai [27,28], and boxing [6] it shows the importance of glycolytic metabolism in these modalities (Figure 1).

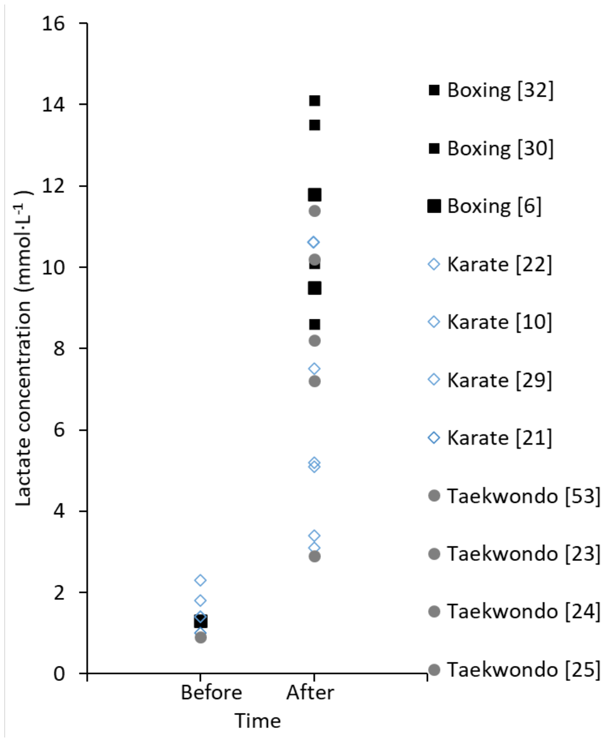


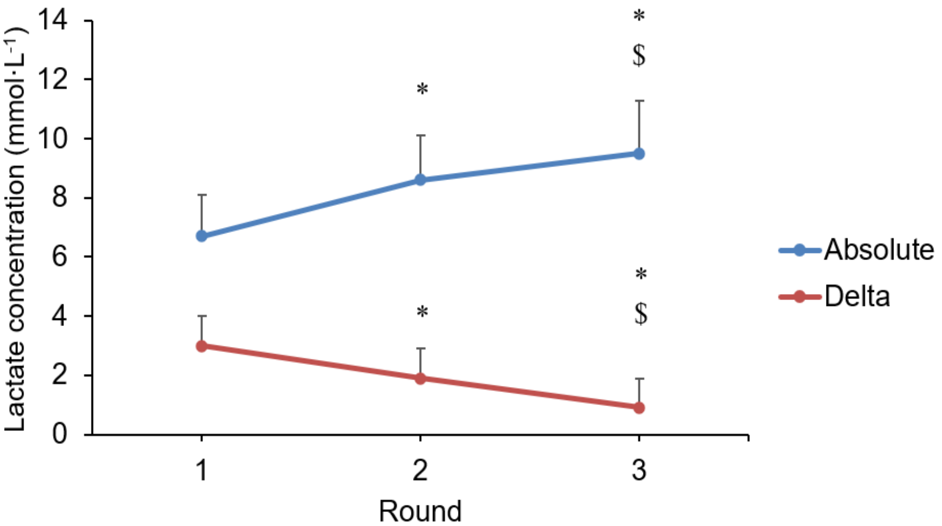
Figure 1: Lactate concentration before and after striking combat simulation.

Note: Some studies only reported the values after the combat simulation

After a karate kumite combat simulation, there is great variability in lactate concentrations, with values between 3.4 ± 1.0 mmol·L^{-1} [10] and 10.6 ± 4.8 mmol·L^{-1} [22]. Therefore, these studies indicate a moderate to high glycolytic demand during karate combat simulations. For example, in karate competitions, the duration of combat is different between genders: 4 minutes for men and 3 minutes for women. In this sense, Doria et al. [22] analyzed the lactate concentration after a combat simulation between men and women. Only 6 karate athletes were evaluated, 3 men and 3 women, after a combat simulation. The results showed that peak lactate concentration after the combat was 10.6 ± 4.8 mmol·L^{-1} for women and 7.5 ± 2.4 mmol·L^{-1} for men, but there was no significant difference between genders for peak lactate concentration. In another hand, Iide et al. [10] measured the lactate concentration during simulated karate sparring with different duration, 2 and 3 minutes. Twelve karate athletes participated in the study. Lactate concentration was significantly higher after 3-minute combat (3.4 ± 1 mmol·L-1) when compared to 2-minute combat (3.1 ± 1 mmol·L-1). Thus, during karate simulation, glycolytic responses are dependent on combat duration. Furthermore, Roschel et al. [29] showed no difference in lactate concentration between the winner (5.1 ± 1.2 mmol·L-1) and defeated (5.2 ± 2.2 mmol·L-1) after a karate combat simulation with 3 minutes of duration. Similarly, Chaabène et al. [21] showed no significant difference in lactate concentration after a karate combat simulation between the winner (11.2 ± 1.5 mmol·L-1). Thus, studies showed a high to moderate glycolytic demand during karate combat simulation, but glycolytic demand is not determinant to the success or failure of athletes during combat.

A typical boxing competition contains 3 x 2-minute rounds, in novice boxers, 4 x 2-minute rounds in intermediate boxers, and 3 x 3 or 4 x 2-minute rounds in open-class boxers by agreement of the coaches and boxers [6]. In amateur boxing, after combat of 3 x 2-minute rounds with 1 minute of recovery between each round, the glycolytic demand is moderate to high with lactate concentration between 9.5 ± 1.8 mmol·L-1 [30] to 11.8 ± 1.6 mmol·L-1 [6] with female amateur boxers showing values around (10.1 ± 2.1 mmol·L-1) in relation to men [31]. In this sense, Smith et al. [31] analyzed the lactate concentration after a boxing combat simulation with different combat duration. During 3 x 2 minutes combats with 1 minute of recovery, lactate concentration after combat was 8.6 ± 3.0 mmol·L-1. On the other hand, during 3 x 3 minutes with 1 minute of recovery, there was an increase in lactate concentration after the combat simulation (9.5 ± 3.0 mmol·L-1). Although the studies did not demonstrate differences between genders in glycolytic demand during boxing combat, the duration of the rounds contributes positively to the increase in lactate concentration.

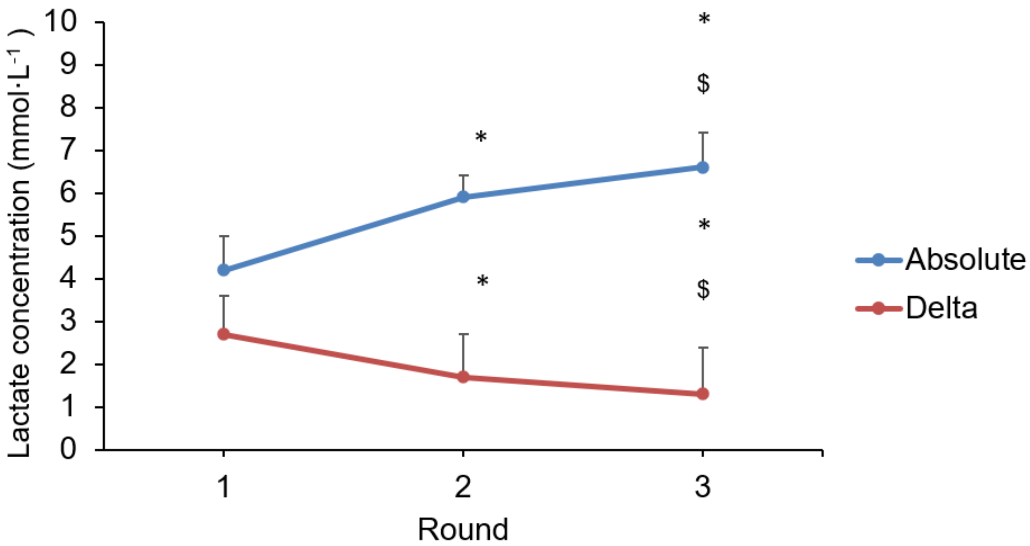
Although studies have shown an increase in absolute values of lactate concentration, throughout the rounds, this does not imply an increase in the glycolytic contribution. In this sense, the authors express the lactate concentration based on delta values, using the difference between peak lactate after each round and lactate concentration at the beginning of the round, when combat sports are divided by rounds. Thus, although there is an increase in lactate concentration, this does not indicate an increase in anaerobic contribution, however, there is a decrease in the glycolytic contribution with the course of the combat. For example, Davis et al. [30] analyzed the lactate concentration throughout the round in a boxing combat simulation, 3 x 2 minutes with 1 minute of recovery between each round. The results showed an increase in lactate concentration with the course of the rounds. However, when delta values were calculated, there was an increase in lactate concentration during the combat simulation. In this way, during boxing combat, the lactate concentration, when analyzed by absolute values, increases based on the number and the duration of rounds, although when values are expressed based on the delta, blood lactate decreases during the combat (Figure 2), indicating that the glycolytic contribution decreases throughout the rounds.



* Different from round 1; $ Different from round 2. All data are presented as mean ± standard deviation.

Figure 2: Lactate concentration during boxing combat simulation. (Adapted from Davis et al. [30]).

In relation to taekwondo combat simulation, Butios and Tasika [24] showed a lactate concentration of 2.9 ± 2.1 mmol·L^{-1} after combat of 3 x 3 minute with 1 minute of recovery between rounds. Furthermore, Campos et al. [25] analyzed the blood lactate concentration during a combat simulation of 3 x 2 minutes with 1 minute of recovery between rounds. The results showed that lactate concentration increased throughout the rounds. However, when lactate concentration was expressed based on delta values, there was a decrease in lactate concentration, indicating a decrease in glycolytic contribution during the combat (Figure 3). Similarly, as demonstrated by Davis et al. [30] with amateur boxing, although the absolute concentration of lactate increases during the combat when analyzed based on the delta, the glycolytic contribution decreases with the number of rounds.



* Different from round 2; $ Different from round 3. All data are presented as mean ± standard deviation.

Figure 3: Lactate concentration during taekwondo combat simulation. (Adapted from Campos et al. [25]).

Ouergui et al. [33] analyzed the effect of combat simulation of kickboxing on the anaerobic capacity of kickboxers. Therefore, 18 kickboxers were evaluated during combat simulation composed of 3 x 2 minutes with 1 minute of recovery between each round. Lactate concentration was measured before and after each round. Furthermore, the upper-body Wingate test was applied after the combat to evaluate the anaerobic capacity, through peak and mean power and fatigue index (%). There was a significant increase in blood lactate throughout the rounds (14.9 ± 0.7 mmol·L^{-1} after the third round), indicating very high participation of glycolytic metabolism during the kickboxing combat simulation. Furthermore, combat simulation was able to decrease the upper-body anaerobic capacity of kickboxers (Table 1). These results demonstrated that there are high glycolytic demand and high request from upper limbs during a kickboxing match.

Table 1: Peak power (PP), mean power (MP), and fatigue index (FI) before and after a kickboxing combat simulation.

	Before	**After**
MP (W.kg^{-1})	4.5 ± 0.5*	4.1 ± 0.5
PP (W.kg^{-1})	5.8 ± 0.6*	5.2 ± 0.6
FI (%)	50 ± 10*	40 ± 10

Data are reported as mean ± standard deviation. * Significant difference ($p < 0,05$) in relation to values after the combat simulation.

Posteriorly, Ouergui et al. [34] investigated whether there was any difference on lactate concentration and anaerobic capacity between kickboxers who win or lose. Twenty athletes of regional and national levels participated in the study and were submitted to a combat simulation comprised by three 2-min rounds with intervals of 1 minute between them. Lactate concentration and upper-body Wingate test performance were measured before and immediately after the combat. The results showed a very high glycolytic (14.0 ± 1.8 mmol·L^{-1}), without significant differences between winners (14.4 ± 1.7 mmol·L^{-1}) and losers (14.0 ± 2.0 mmol·L^{-1}). Furthermore, upper-body Wingate test performance was significantly lower after the combat, but it did not differ between winners and losers (Table 2). Thus, this suggests a similar anaerobic demand for both winning and losers kickboxers, whereas the decrease in peak power could be explained by the great anaerobic upper-body solicitation during the combat, which impaired subsequent performance in the Wingate test.

Table 2: Peak power (PP) and mean power (MP) before and after kickboxing competition in relation to combat outcome.

	Winners	**Losers**	**Overall**
PP (W.kg^{-1})			
Before	6.0 ± 1.2	5.1 ± 1.0	5.6 ± 1.2
After	4.0 ± 1.0*	3.4 ± 0.9*	3.7 ± 1.0*
Δ	2.1 ± 0.9	1.7 ± 0.6	1.9 ± 0.8
MP (W.kg^{-1})			
Before	3.6 ± 0.9	3.5 ± 0.9	3.6 ± 0.9
After	2.1 ± 0.5*	1.9 ± 0.6*	1.9 ± 0.6*
Δ	1.6 ± 1.0	1.6 ± 0.7	1.6 ± 0.8

Data are presented as mean ± standard deviation. * Different from before ($P < 0.001$). Abbreviation: Δ, difference between before and after combat.

Several studies analyzed the lactate concentration during combat simulation of Brazilian Jiu-Jitsu [35-38], judo [39-42], and wrestling [3,43-45]. These studies showed that glycolytic metabolism is important in these modalities. During Brazilian Jiu-Jitsu combat the glycolytic demand is moderate. For example, Andreato et al. [35] reported high values of lactate concentration (11.9 ± 5 mmol·L^{-1}) after a combat simulation of 7 minutes.

For example, Andreato et al. [36] analyzed the lactate responses in Brazilian jiu-jitsu athletes during combats of varied duration. For this, 10 athletes were submitted to combat simulations lasting 2-min, 5-min, 8-min, and 10-min. The sequence of combats was counterbalanced, and athletes had a 60-min recovery between each combat simulation. The lactate concentration was measured before and immediately after each combat of different duration. The absolute values of lactate concentration were significantly higher after combat with 2-min (6.2 ± 1.2 mmol·L^{-1}), 5-min (7.4 ± 1.9 mmol·L^{-1}), 8-min (8.1 ± 2.3 mmol·L^{-1}), and 10-min (10.1 ± 1.4 mmol·L^{-1}) duration in relation to baseline values (1.1 ± 0.3 mmol·L^{-1}). However, when the absolute values were reported, the lactate after the combat with 10-min (8.7 ± 1.6 mmol·L^{-1}) was significantly higher when compared to 2-min (5.4 ± 1.2 mmol·L^{-1}) and 5-min (6.4 ± 1.8 mmol·L^{-1}) combats. These results corroborate with the literature that demonstrated a moderate to high glycolytic activation during Brazilian jiu-jitsu combats. Moreover, this dynamic is influenced by time, i.e., the longer the combat duration, the higher the glycolytic demand. On the other hand, when lactate concentration was normalized by the effort time, the dynamic was different, a greater variation in lactate concentration was observed in shorter matches, 2-min (2.7 ± 0.6 mmol·L^{-1}) and 5-min (1.3 ± 0.4 mmol·L^{-1}), when compared to 8-min (0.9 ± 0.3 mmol·L^{-1}) and 10-min (0.9 ± 0.3 mmol·L^{-1}) combats. Thus, the higher activation in the longer combats may reflect a cumulative effect during combat. In other words, the lactate production rate during combat was greater than the removal rate, especially in the initial minutes.

On the other hand, Da Silva et al. [37] investigated if lactate concentration after a simulation of Brazilian Jiu-Jitsu combat could be different for athletes with different competitive levels. Thus, 14 Brazilian Jiu-Jitsu athletes were divided into two groups: 7 advanced (brown and black belts) and 7 no-advanced (blue to purple belts). Combat simulation was composed of 10 minutes. The results showed a high glycolytic demand after the combat simulation (10.3 ± 2.6 mmol·L^{-1}). However, there was no significant difference between the two groups advanced and no-advanced (10.4 ± 3.6 mmol·L^{-1} and 10.2 ± 1.3 mmol·L^{-1}, respectively). Thus, the competitive level does not influence the glycolytic demand during Brazilian Jiu-Jitsu combat simulation.

In this sense, Franchini and da Silva [46] showed that glycolytic demand was not different after Brazilian jiu-jitsu when winning and losing athletes were compared. The peak lactate concentration after the combat was significantly higher (8.79 ± 2.34 mmol L−1) when compared to values before combat (2.19 ± 0.55 mmol·L−1). However, the lactate concentration of winners (7.83 ± 2.47 mmol·L−1) and losers (9.76 ± 1.90 mmol·L−1) was similar. Thus, our results confirm the notion that glycolytic activation does not seem to be decisive for victory/defeat in Brazilian jiu-jitsu athletes.

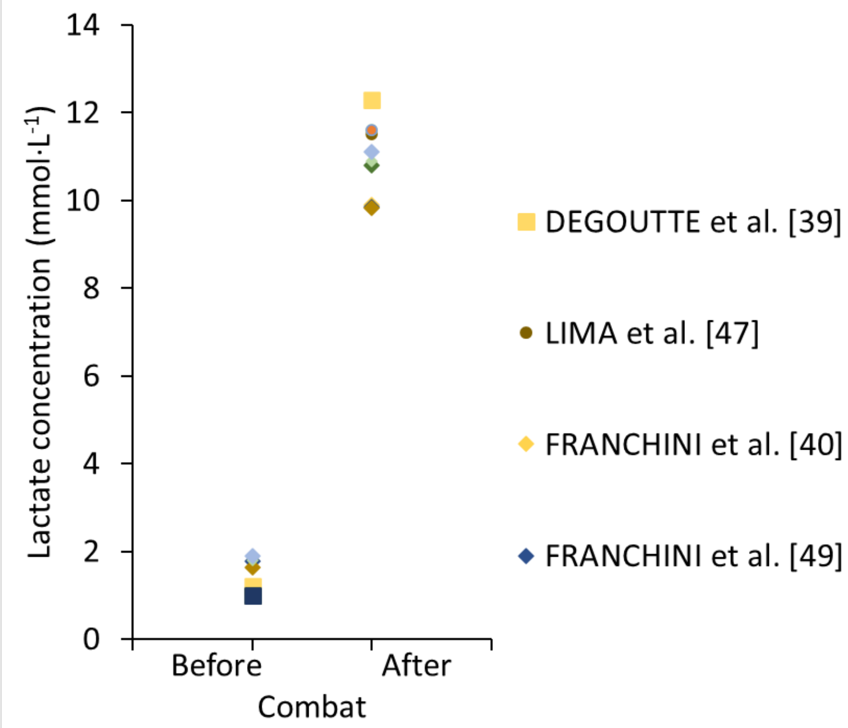
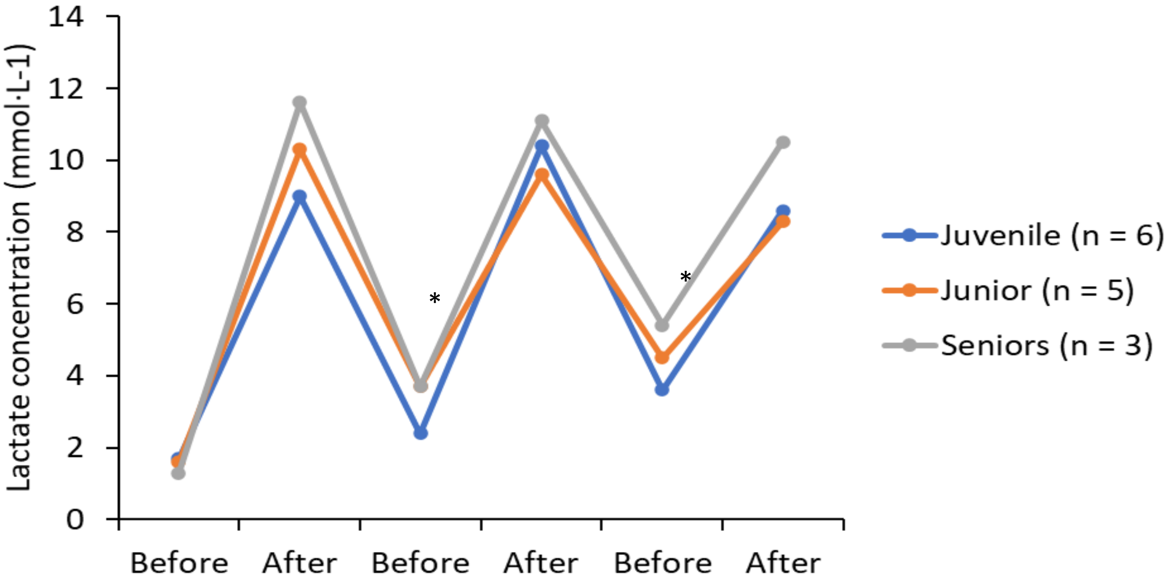


Figure 4: Lactate concentration before and after judo combat simulation.

The glycolytic demand is high (10 mmol·L-1) after a judo combat simulation (Figure 4). Degoutte et al. [39] reported a lactate concentration of 12.3 ± 0.8 mmol·L-1 when evaluated 2 minutes after a combat simulation of 5 minutes. On the other hand, Lima et al. [47] investigated if lactate concentration could be different after judo combat simulation with different duration: 1.5, 3, and 5 minutes. The results of the study showed that lactate concentration after the combat simulation did not present a significant difference between combats with different durations: 1.5 minutes (11.5 ± 0.76 mmol·L-1), 3 minutes (11.6 ± 1.8 mmol·L-1), and 5 minutes (11.6 ± 2.6 mmol·L-1). It suggests the glycolytic demand may occur in the initial stage of combat.

In judo competitions, the medalists perform 5-7 fights in a single day. In this sense, some studies analyzed lactate concentration during several judo combats. Franchini et al. [48] analyzed the lactate concentration after 3 judo combats of 4 minutes duration with a minimum interval of 20 minutes between each combat. For that, 15 judo athletes were evaluated and divided into 3 groups according to their category: 6 juvenile, 5 junior, and 4 seniors. The results showed that there was an increase in peak lactate concentration after each combat, but without differences between category and combats. On the other hand, lactate concentration after the first combat (1.6 ± 0.6 mmol·L-1) was significantly lower in relation to second (1.3 ± 1.9 mmol·L-1) and third (4.3 ± 2.2 mmol·L-1) combats (Figure 5). Thus, these results show that a 20 minutes period between each combat was not enough for the lactate concentration to return to resting levels.

Furthermore, Franchini et al. [49] analyzed the lactate concentration after two 5-min combat simulations with 15 minutes of recovery between them. The peak lactate concentration after the first combat was significantly higher (12.6 ± 5 mmol·L-1) when compared to the second combat (11.62 ± 4.79 mmol·L-1). It indicates a lower glycolytic demand as combat is repeated. In a series of studies [50-52] analyzed the lactate concentration during four 5-min judo combat simulations, interspersed with 15 minutes of passive recovery between each combat. The results showed that the lactate concentration was significantly lower after the fourth combat (12.6 ± 3.5 mmol·L-1) when compared to values after the first combat (14.6 ± 4.0 mmol·L-1), without difference between other combats [51], whereas Bonitch-Góngora et al. [52] reported an increase in lactate concentration after each combat, with higher significantly values after the first (18.1 ± 4.4 mmol·L-1) and the second combat (16.9 ± 3.5 mmol·L-1) in relation to the third (15.2 ± 4.4 mmol·L-1) and fourth combats (14.5 ± 3.5 mmol·L-1). Recently, Bonitch-Góngora et al. [50] reported a progressive decrease in lactate along with the judo combats: after the first (17.8 ± 4.3 mmol·L-1), second (16.6 ± 3.5 mmol·L-1, third (15.6 ± 4.8 mmol·L-1) and fourth (14.2 ± 3.7 mmol·L-1) combats. Taken together, these studies indicate decreased glycolytic activation when successive combats are performed.



* Different from before first combat.

Figure 5: Lactate concentration before and after combat simulation in juvenile, junior, and seniors' athletes. (Adapted from Franchini et al. [48]).

Karninčić et al. [45] investigated the influence of competitive level on lactate concentration during Greco-Roman wrestling combat simulation. 20 wrestlers were divided into 10 from the national team and 10 from a club team. The combat was composed of 3 rounds of 2 minutes intercepted by 30 seconds between each round. There was a high glycolytic demand after the combat, but lactate concentration after the combat was no significant differences between elite (12.55 ± 1.8 mmol·L-1) nonelite (13.23 ± 1.47 mmol·L-1).

After that, Karninčić et al. [44] investigated the influence of weight category on lactate concentration after wrestling combat. 60 youth wrestlers were divided into three weight groups: 20 lightweight, 20 middleweight, and 20 heavyweights. The wrestling combat was composed of 3 rounds of 2 minutes with 30 seconds of rest between each round. Lactate concentration increased significantly after the combat, but there were no significant differences in the lactate concentration between lightweight (11.7 ± 3.1 mmol·L-1), middleweight (10.8 ± 2.5 mmol·L-1), and heavyweight (10.8 ± 2.1 mmol·L-1).

Furthermore, Karninčić et al. [43] analyzed the influence of the age categories in the lactate concentration of wrestlers. The study was conducted on a sample of 30 young wrestlers. The sample was divided into three age categories: 10 boys (12.7 ± 0.5 years, 10 cadets (15.6 ± 0.5 years), and 10 juniors (18.2 ± 1.1 years). The combat was composed of 3 rounds of 2 minutes with 30 seconds of rest between each round. The results showed a high glycolytic demand in all categories after the combat. There was no significant difference in the lactate concentration after the combat between juniors (11.2 ± 1.3 mmol·L-1) and cadets (12.0 ± 2.5 mmol·L-1). However, the lactate concentration was significantly lower for boys (9.1 ± 1.6 mmol·L-1) when compared to juniors and cadets. The authors justified these results may be caused by maturational factors or the type of training of athletes. The juvenile athletes were in the process of learning wrestling techniques; thus, the developments of the motor and functional abilities are not of primary interest.

2.2 Lactate concentration after competition simulation

Several studies have been investigated the lactate responses after a competition simulation during karate [20,21,50,51] and taekwondo [17,51-53] combats (Figure 6). Beneke et al. [20] analyzed the lactate concentration during a karate competition simulation, composed of 4 combats. Delta values demonstrated a reduction in the lactate concentration after the first (5.9 ± 1.6 mmol·L^{-1}), second (5.0 ± 1.2 mmol·L^{-1}), third (3.3 ± 1.2 mmol·L^{-1}), and fourth (2.2 ± 1.5 mmol·L^{-1}) combats. Furthermore, the values after the third and fourth combats were significantly lower when compared to the first and second combats. These results suggest that after the third combat the glycolytic contribution was reduced and a possible increase in the oxidative contribution.

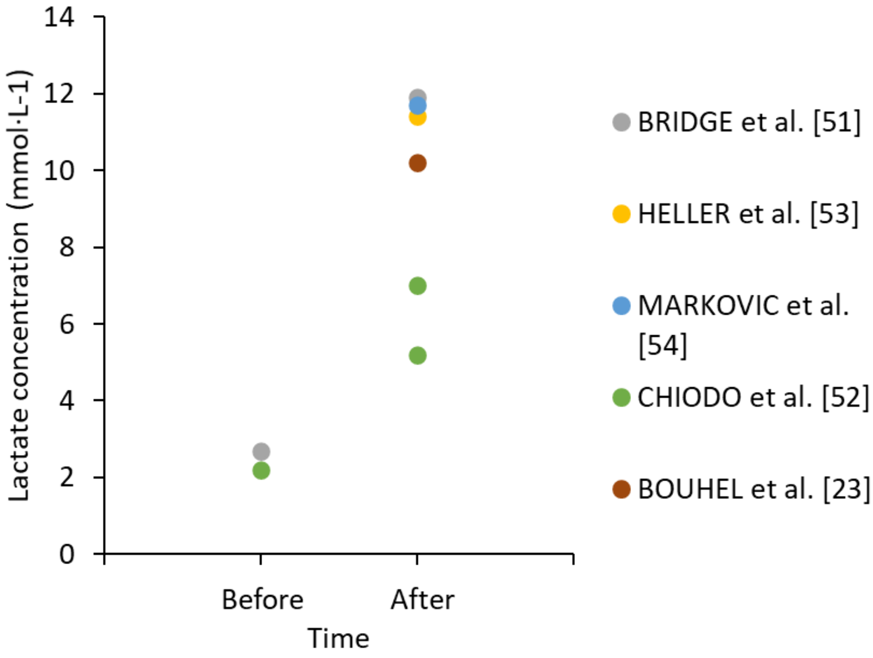


Figure 6: Lactate concentration before and after taekwondo combat simulation.

Tabben et al. [50] analyzed the lactate concentration before and after the international karate Kumite competition (International Karate Dutch Open, Rotterdam 2010). Seven karate athletes (3 women and 4 male) were evaluated. The duration of combat was 3 minutes for men and 2 minutes for women. The lactate concentration was measured before the first combat and immediately after each combat. There was a significant increase in the lactate concentration after each combat, but there was no significant difference between the combat and the genders (Figure 7). Furthermore, the values reported by Tabeen et al. [50] were higher than reported during a karate combat simulation [20]. This difference can be caused by the methodological reasons between these two studies, combat simulation [20] and competition simulation [50]. In this sense, the glycolytic demand is higher during international competitions in relation to combat simulation.

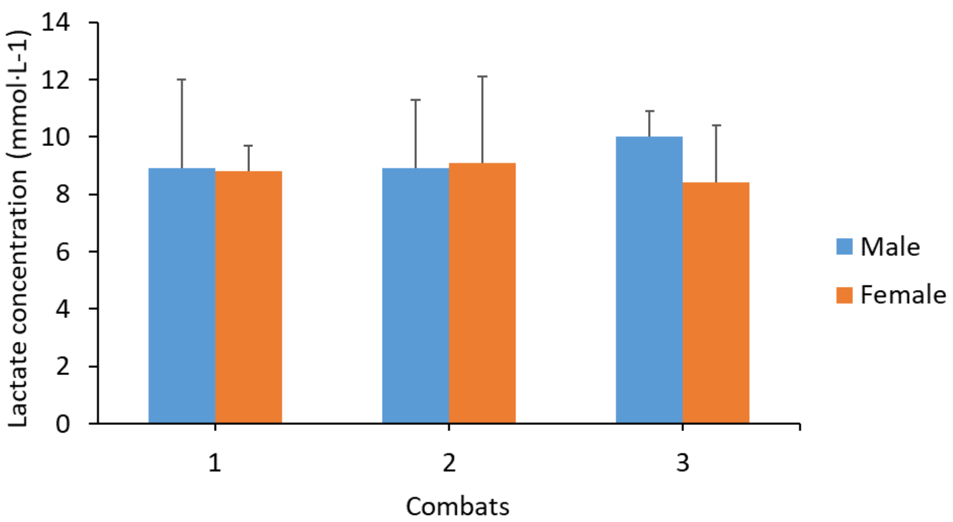


Figure 7: Lactate concentration during international karate Kumite competition. (Adapted from Tabben et al. [50]).

Moreover, Chaabène et al. [21] compared the lactate concentration during official and simulated karate combat. 10 high-level karate athletes participated in this study. The combats were composed in 3 minutes. The lactate concentration was measured before and 3 minutes post-combat. The results showed a higher lactate concentration after official combat when compared to combat simulation (Figure 8). These results showed that official combats demand a higher glycolytic participant in relation to combat simulation, probably because of greater intensity during the official combat.

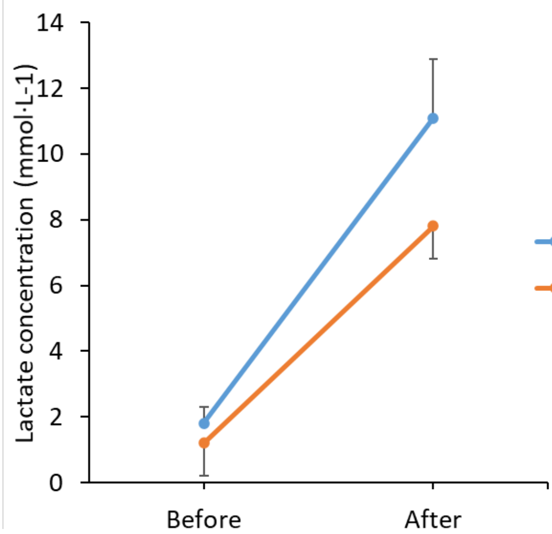


Figure 8: Lactate concentration before and after official and simulated karate combat. (Adapted from Chaabène et al. [21]).

During taekwondo competitions, Heller et al. [53] demonstrated a lactate concentration of 3.34 mmol·L^{-1} after a simulation of competition, composed of one combat of 2 rounds of 2 minutes with 1 minute of recovery between each round. On the other hand, Bridge et al. [51] analyzed the lactate concentration during a simulation of competition, 3 rounds of 2 minutes with 30 seconds of the interval between each round. The results showed an increase in the lactate concentration after the first (7.5 ± 1.6 mmol·L^{-1}), second (10.4 ± 2.4 mmol·L^{-1}), and third (11.9 ± 2.1 mmol·L^{-1}) rounds. However, after the second and third rounds, the lactate concentration was significantly lower than compared with values after the first round. In another study, Matsushighe et al. [17] compared the relationship between lactate concentration and competitive success. The results showed an increase in the lactate concentration after the competition simulation, but there was no significant difference after the combat between winners (7.8 ± mmol·L^{-1}) and defeated (7.2 ± 3.4 mmol·L^{-1}). Furthermore, Markovic et al. [54] measured the lactate concentration after competitive taekwondo combat performed by elite women. The results showed an increase in the lactate concentration 3 minutes after the competition simulation (11.7 ± 1.8 mmol·L^{-1}). Moreover, Chiodo et al. [52] analyzed if gender could influence the lactate concentration after a taekwondo competition simulation. The results showed an increase in the lactate concentration after the combat, but there were no significant differences between gender (Figure 9).

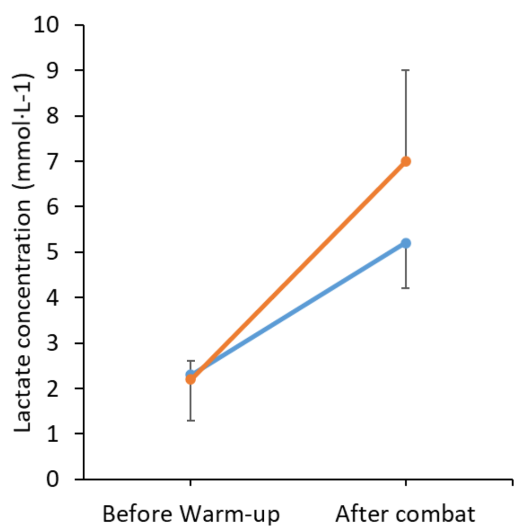


Figure 9: Lactate concentration before and after taekwondo combat simulation. (Adapted from Chiodo et al. [52]).

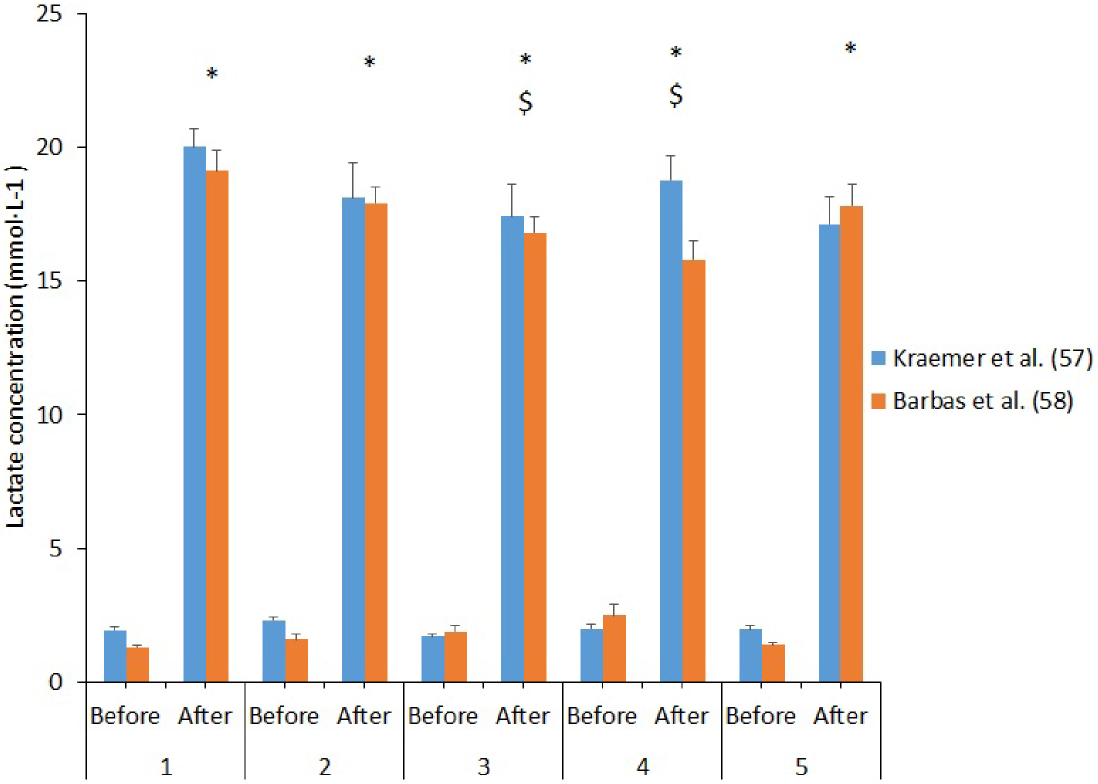
Several studies have analyzed the lactate concentration during judo [42,55,56] and wrestling [57,58] competition simulations. Furthermore, some studies analyzed the lactate concentration during official competition of wrestling [3] and Brazilian Jiu-Jitsu [7,35,36]. For example, Andreato et al. [35] analyzed the lactate concentration after a regional competition of Brazilian Jiu-Jitsu. 35 male Brazilian Jiu-Jitsu athletes graded from white to brown belt participated in the study. The lactate concentration was measured before and after the combat. The results showed a moderate glycolytic demand, with values of 10.1 ± 8 mmol·L^{-1} after the regional competition. Furthermore, Andreato et al. [36] evaluated 12 Brazilian Jiu-Jitsu athletes' blue belt, which participated in a regional competition of Brazilian Jiu-Jitsu. The lactate concentration was measured before and after the combat. Although the lactate showed a moderate glycolytic demand (6.2 ± 2.3 mmol·L^{-1}), these values were lower than reported by Andreato et al. [35]. A possible explanation for differences between studies may be caused by the different graduation of the athletes, Andreato et al. [35] analyzed athletes more graduated in comparison to athletes analyzed by Andreato et al. [36].

Franchini et al. [55] described the glycolytic demand during a simulated judo competition. For this, ten judo athletes were submitted to a simulated competition (four matches separated by 15-min intervals). The lactate concentration was measured before and after each combat. The results showed that lactate concentration was significantly higher after combats when compared to values before combats. Furthermore, lactate concentration before the third combat was significantly higher compared to before the first combat, while lactate concentration after the second combat was significantly higher in relation to values after the third and fourth combats. Thus, the glycolytic demand decreased as the athlete performs consecutive combats during a typical competition day.

Recently, Franchini et al. [56] investigated the effects of different fatigue levels on glycolytic demand during judo combats. For this, 12 judo athletes completed three 4-minute combats interspersed by 15-min passive recovery against the same opponents in three different conditions: after warm-up (control condition), after a regular training session (TS) (totaling 90 minutes), and after a high-intensity interval exercise (HIIE) session (2 blocks of 10 sets of 20-second all-out *uchi-komi*, with 10-seconds interval between sets and 5-minutes interval between blocks). Lactate concentration was measured before and after each match. Furthermore, delta lactate was calculated as lactate peak minus lactate before the combat. The results showed that peak lactate was significantly higher in the HIIE compared with the TS, with higher values after combat 1 in HIIE (9.51 ± 2.79 mmol·L^{-1}) compared to post-combat 1 in the TS condition (5.68 ± 1.56 mmol·L^{-1}). The delta values were significantly higher in the control condition in relation to the HIIE condition, with higher values for combat 1 of the control condition (6.00 ± 2.05 mmol·L^{-1}) compared with combats 2 (3.60 ± 1.71 mmol·L^{-1}) and 3 (2.07 ± 1.87 mmol·L^{-1}) of the same condition. Furthermore, delta values of blood lactate for the combat 1 (0.07 ± 1.71 mmol·L^{-1}) in the HIIE was lower than combats 2 (2.75 ± 1.64 mmol·L^{-1}) and 3 in the same condition (3.23 ± 1.51 mmol·L^{-1}) and combat 1 in the TS condition (2.62 ± 1.22 mmol·L^{-1}).

Wrestling events are organized in a tournament format thereby requiring athletes to compete in multiple matches for hours of a few consecutive days. In this sense, Kraemer et al. [57] and Barbas et al. [58] analyzed the lactate concentration during freestyle and Greco-Roman wrestling competitions, respectively. Kraemer et al. [57] investigated the lactate concentration responses to consecutive two days of wrestling in a tournament format after a typical period of cut weight. Therefore, athletes had to reduce their body weight during the week before the competition. The 2 days wrestling tournament consisted of five freestyle matches (three matches on day 1 and two matches on day 2. Each match was a 5-min Olympic freestyle match. Before and after each match athletes performed a vertical jump to evaluate the lower body power. The results showed a very high lactate concentration during the competition (Figure 10). However, the lower body power was significantly reduced after the fourth combat (4,318.4 ± 344.1 W) when compared to values before the first, second, and third combats (4,758.5 ± 361.5 W, 4,869.1 ± 278.1 W, and 5,052.7 ± 344.1 W, respectively).

Similarly, Barbas et al. [58] analyzed the lactate concentration of well-trained wrestlers to a simulated one-day tournament of Greco-Roman wrestling following a typical weight loss regimen. For this, athletes reduced approximately 6% of the body during the week that preceded the competition. The tournament consisted of five matches scheduled according to the official regulation of the International Wrestling Federation (FILA). Each match was composed by three 2-min rounds, 30-s breaks between rounds. The second match was performed 80-90 minutes after the first, the third 60-70 minutes after the second, the fourth 30-40 minutes after the third, and the fifth 5-6 hours after the fourth. The results showed a very high glycolytic demand after each combat during the competition. However, after the third and fourth combats, the lactate concentration was significantly reduced when compared to values after the first combat (Figure 10). Furthermore, the vertical jump was reduced before and after each combat. However, the vertical jump before the fourth combat (34.9 ± 2.3 cm) was significantly lower when compared to values before the first combat (41.7 ± 1.9 cm). Thus, the reduction in the lactate concentration and concomitant reduction in the vertical jump demonstrates that 30-40 minutes of recovery between combats are insufficient to recover the performance.



* Significantly higher when compared to before combat in Greco-Roman and Freestyle Wrestling.
$ Significantly lower when compared to after second combat in Greco-Roman and Freestyle Wrestling.

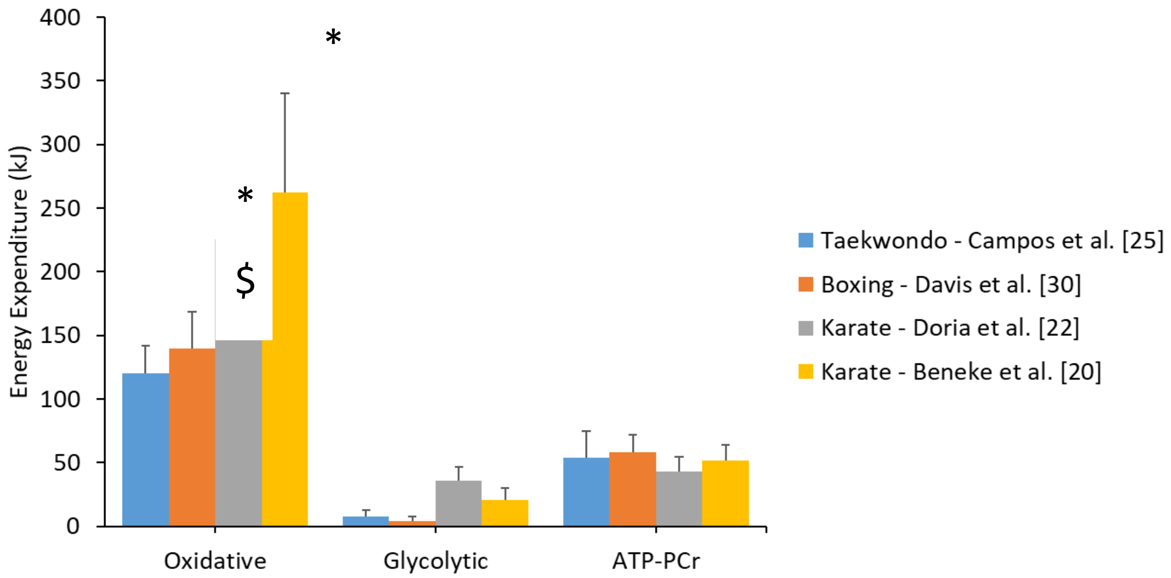
Figure 10: Lactate concentration during Greco-Roman and freestyle Wrestling, respectively (Adapted from Barbas et al. [58] and Kraemer et al. [57]).

Moreover, Del Vecchio et al. [13] analyzed the lactate concentration during an official competition, the 2005 Jiu-Jitsu World Cup. The results showed a high glycolytic demand (10.2 ± 1.5 mmol·L^{-1}) 2 minutes after the combat. Additionally, Nilsson et al. [3] analyzed the lactate concentration after the 1998 Greco-Roman wrestling World Championship. The results showed a very high glycolytic demand (14.8 ± 2.8 mmol·L^{-1}) after the competition. Furthermore, when lactate concentration was analyzed based on combat duration, there was a significant difference between combats of long duration (442 ± 56s; 15.7 ± 2.4 mmol·L^{-1} than in those of short duration (175 ± 51s; 13.6 ± 2.8 mmol·L^{-1}).

2.3 Energy systems contribution

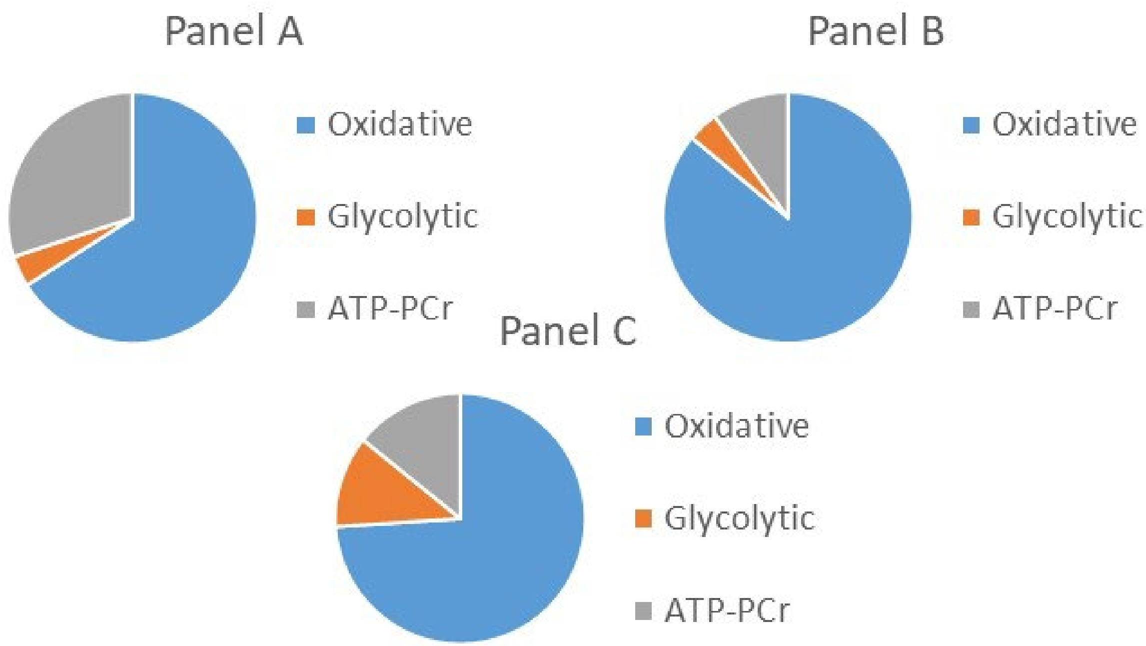
In general, combat sports are classified as high-intensity intermittent activities during which glycolytic metabolism is determinant [1]. In this sense, several studies have been evaluated the energy system contribution during combat of karate [20,22], taekwondo [25], and boxing [30], through the method in which is possible to separate the contribution of glycolytic and ATP-PCr metabolism. However, Crisafulli et al. [28] quantified the aerobic and anaerobic contribution during a combat simulation of Muay Thai. In relation to judo combat, one study analyzed the energy system contribution during a combat simulation [59] and specific exercise training, as *nage-komi* [60] and *uchi-komi* [61].

When analyzed the energy predominance during combat, aerobic metabolism is the predominant absolute source of energy, following by anaerobic ATP-PCr and glycolytic metabolism, but without significant difference between the absolute contribution of ATP-PCr and glycolytic metabolism. (Figure 11). Similarly, the contribution relative to total work done (%) is predominantly aerobic, following by ATP-PCr and glycolytic metabolisms, but without significant differences between ATP-PCr and glycolytic contributions during combat simulation of taekwondo, boxing, and karate (Figure 13).



* Significantly higher in relation to glycolytic contribution. $ Significantly higher in relation to ATP-PCr contribution.

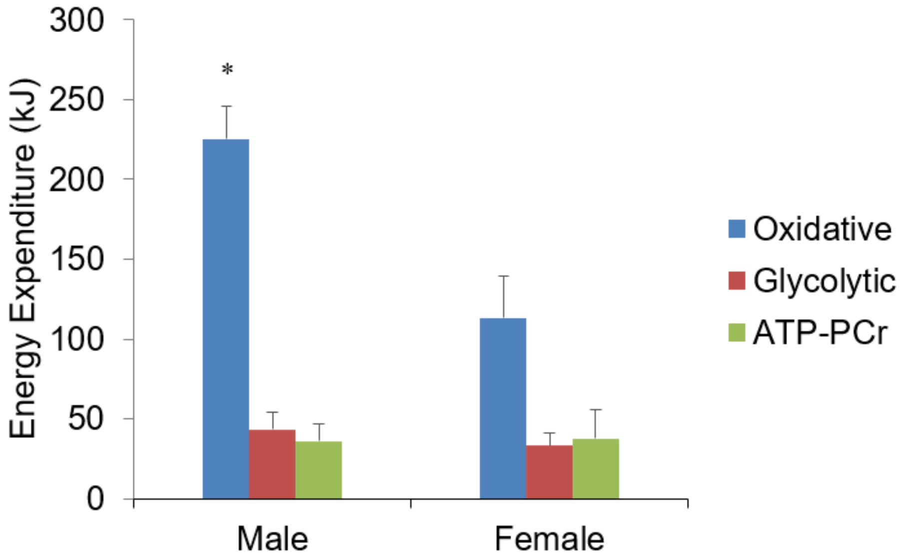
Figure 11: Oxidative, Glycolytic, and ATP-PCr energy sources taekwondo, boxing, and karate combat simulations. Absolute contribution (kJ).



Taekwondo (Panel A, adapted from Campos et al. [25]), Boxing (Panel B, adapted from Davis et al. [30]) and Karate (Panel C, adapted from Doria et al. [22]).

Figure 12: Relative energy contribution (%) during combat simulation.

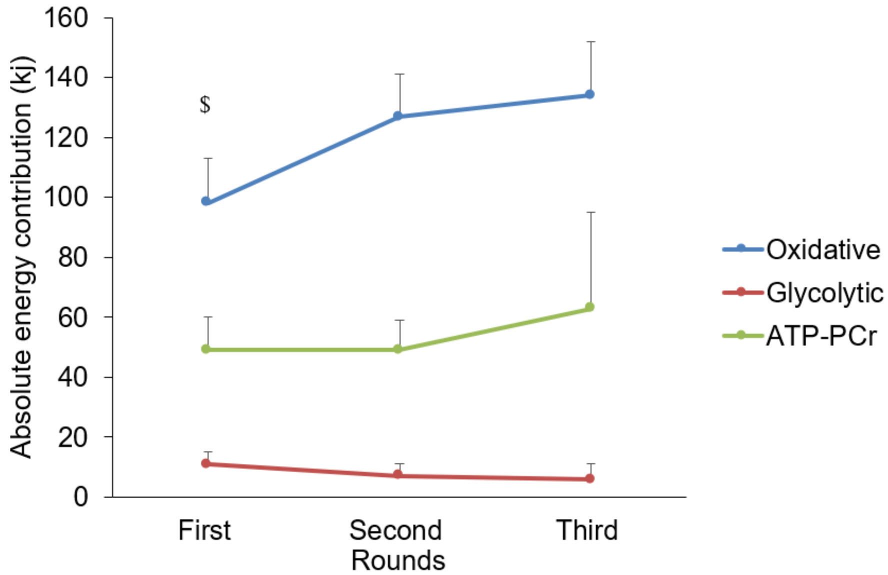
Doria et al. [22] analyzed the influence of gender on the energy system contribution during karate combat. The results demonstrated a predominance of the absolute aerobic metabolism during the combat simulation, with men presenting a higher aerobic metabolism in relation to women. Furthermore, there was no significant difference between men and women in relation to absolute glycolytic and ATP-PCr contributions (Figure 13). Similarly, the relative aerobic contribution related to total work done (%) was significantly higher in men when compared to women, following by ATP-PCr and glycolytic contribution, but without significant differences between genders.



* Significantly higher in relation to female.

Figure 13: Energy expenditure during karate combat simulation (Adapted from Doria et al. [22).

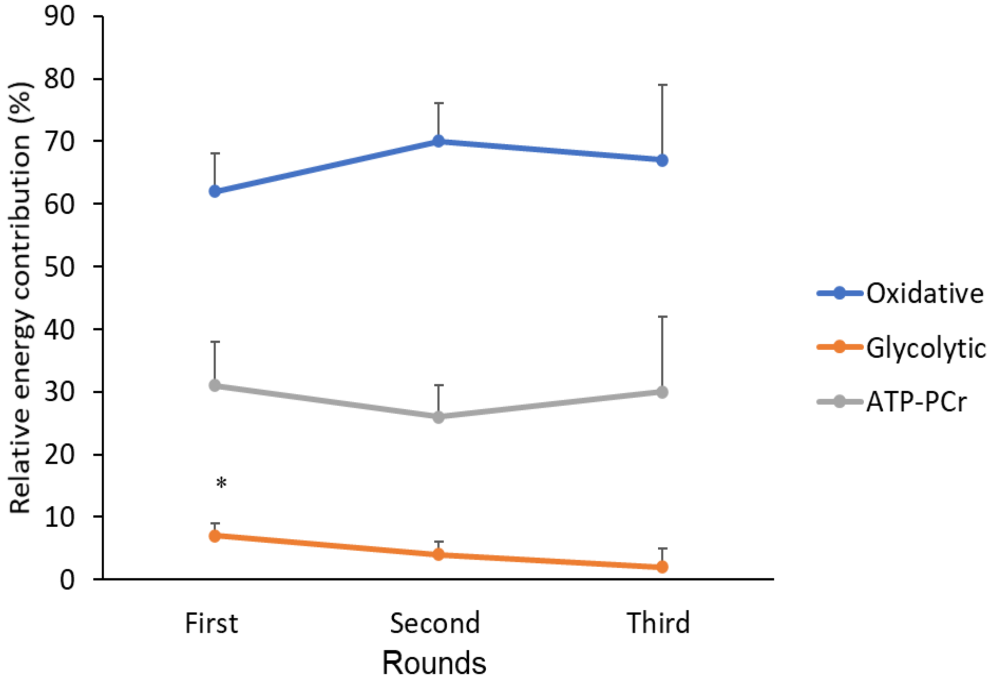
Aerobic metabolism is predominant during a combat simulation boxing (3 rounds of 2 minutes with 1 minute of recovery between each round). Davis et al. [30] demonstrated aerobic metabolism is predominant during a combat simulation, following the ATP-PCr and glycolytic metabolism (Figure 11). When values were expressed by the percentage of total work performed, the relative contribution of oxidative, ATP-PCr, and glycolytic metabolism was 77%, 19%, and 4%, respectively (Figure 12).



$ Significantly lower when compared to second and third rounds. All data are presented as mean ± standard deviation.

Figure 14: Absolute energy contribution (kJ) during taekwondo combat simulation. (Adapted from Campos et al. [25]).

Furthermore, Campos et al. [25] analyzed the energy system contribution during a combat simulation of taekwondo, 3 rounds of 2 minutes with 1 minute of recovery between each round. The results that absolute aerobic metabolism increased significantly over the rounds with lower values in the first round when compared to the second and third rounds. In relation to the glycolytic contribution, there was a decrease over the rounds, with significantly lower values after the first round in relation to the third round. However, there was no significant difference in the ATP-PCr contribution over the rounds (Figure 14). When analyzed the system contribution in relation to total work done, there were no significant differences in the aerobic and ATP-PCr contribution, but the glycolytic contribution decreased significantly over the rounds, with higher values in the first round when compared to the second and third (Figure 15).



* Significantly higher in relation to the third round. All data are presented as mean ± standard deviation.

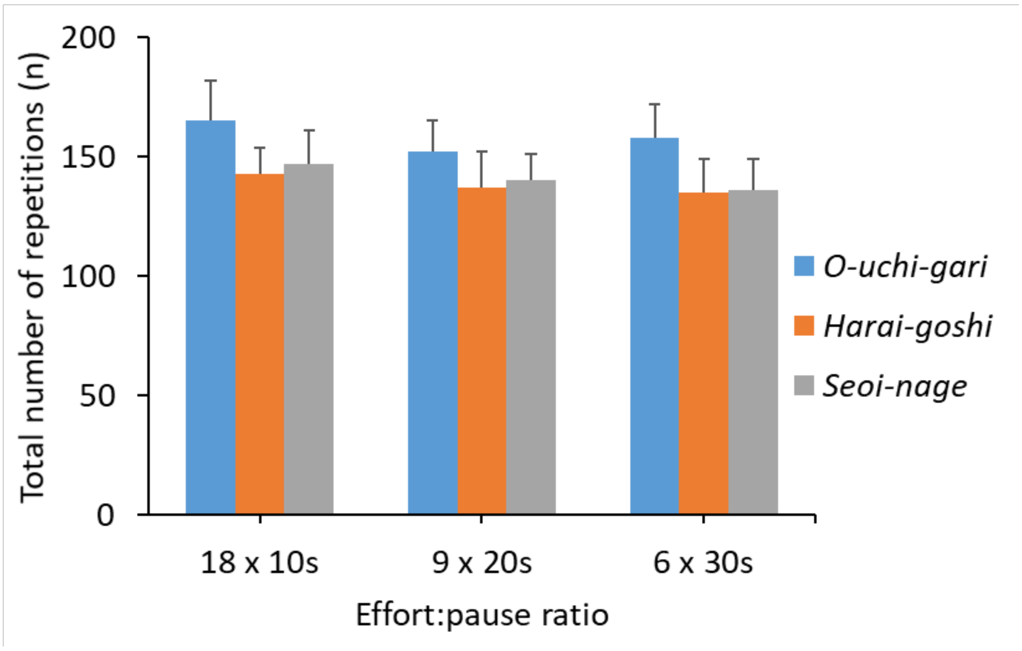
Figure 15: Relative energy contribution during taekwondo combat simulation. (Adapted from Campos et al. [25]).

Additionally, Crisafulli et al. [28] utilized another method to evaluate the energy demand during simulation combat of Muay Thai. Therefore, 10 athletes, 6 of the international level and 4 of the national level performed a combat simulation consisted of 3 rounds of 2 minutes, with 1 minute of recovery between each round. During the combat, the oxygen uptake and carbon dioxide production (CO2) were measured to obtain an index of anaerobic glycolysis, but this method is not possible to separate the anaerobic contribution into lactic and alactic. The results showed a linear increase with higher values of CO2 in the first and second rounds (307.3 ± 77.5 $mL.min^{-1}$ and 405.8 ± 95.5 $mL.min^{-1}$, respectively), but CO2 values decrease in the third round (195.7 ± 93.6). In this sense, these results demonstrated that glycolytic metabolism was predominant in the first round, while oxidative metabolism was predominant in the second and third rounds. However, the method utilized to calculated the energy anaerobic demand, through the CO2 production, does not allow to separate what was derived from lactic or alactic anaerobic metabolism.

Franchini et al. [60] analyzed the energy system contribution in three different judo techniques: *o-uchi-gari*, *morote-seoi-nage* and *harai-goshi*. Twelve black belt judo athletes participated in this study. Each athlete was submitted to a 5-minute protocol for each technique, with a 40-60 minutes interval. During each session, the athlete applied the technique, throwing an opponent on time at each 15s. This pattern was based on the mean time between throwing attempts during the competition and on the total match duration, respectively. The absolute ATP-PCr contribution was significantly higher during *seoi-nage* (42.2 ± 2 kJ) and *harai-goshi* (43.2 ± 2 kJ) when compared to *o-uchi-gari* (31.2 ± 2 kJ). Similarly, the relative ATP-PCr contribution was significantly higher during *seoi-nage* (16.3 ± 2.8 %) and *harai-goshi* (16.1 ± 2.7 %) when compared to *o-uchi-gari*

(16.1 ± 2.7%). The absolute oxidative contribution was significantly higher during *seoi-nage* (223 ± 66 kJ) when compared to *o-uchi-gari* (196 ± 74 kJ). No difference was observed in the relative oxidative contribution among techniques. There was also no difference in both relative and absolute glycolytic contribution among techniques. However, total energy expenditure is higher during *seoi-nage* (273 ± 86 kJ) in relation to *o-uchi-gari* (237 ± 99 kJ).

Understanding the physiological responses to the most common judo training modalities may help to improve the prescription and monitoring of training programs. In this sense, Franchini et al. [61] analyzed the physiological response and performance with different judo techniques and time-structured *uchi-komi* (technique entrance) protocols. Ten judo athletes which were submitted to nine all-out *uchi-komi* sessions. Three techniques (*o-uchi-gari*, *seoi-nage*, and *harai-goshi*) and 3 different time structures (18 x 10 seconds/10 seconds of the interval, 9 x 20 seconds/20 seconds of interval and 6 x 30 seconds/30 seconds of the interval). The authors evaluated the performance through the number of throwing performed. There was no significant difference in time structure for the number of technique repetitions (Figure 16). This result suggests that when a 1:1 effort-pause ration and all-out effort are used, judo athletes can perform the same number of repetitions during *uchi-komi*.



All data are presented as mean ± standard deviation.

Figure 16: Number of repetitions during *uchi-komi* using 3 different techniques and 3 times structures (Adapted from Franchini et al. [61]).

Furthermore, there was no significant difference for time structure or technique on the absolute energy expenditure. However, *o-uchi-gari* resulted in a lower total energy expenditure per repetition when compared to *seoi-nage* (Table 3). This result may be a consequence of the movement pattern, especially because of the requirement for trunk rotation and knee flexion during *seoi-nage*, which increase the length of time required to perform a single repetition. Thus, the use of *uchi-komi* as a training stimulus may be a better training stimulus because it is specific to the sport.

Table 3: Absolute (kJ) and relative (%) energy expenditure during uchi-komi session using different technique structures (Values expressed as mean ± standard deviation); Adapted from Franchini et al. [61]).

	O-uchi-gari			***Harai-goshi***			***Seoi-nage***		
	18 x 10s	9 x 20s	6 x 30s	18 x 10s	9 x 20s	6 x 30s	18 x 10s	9 x 20s	6 x 30s
Total (kJ)	32.4 ± 49.3	316.6 ± 50.7	348.3 ± 31.7	314.6 ± 34.7	314.2 ± 4.5	329.1 ± 0.1	340.9 ± 33.3	334.9 ± 9.6	343.4 ± 2.8
Total (%)	2.01 ± 0.42*	2.10 ± 0.40*	2.22 ± 0.29*	2.21 ± 0.26	2.31 ± 0.52	2.45 ± 0.24	2.34 ± 0.28	2.40 ± 0.27	2.53 ± 0.43

* Significant lower ($p < 0.05$) in relation to *seoi-nage.*

To characterized the metabolic demand of judo combat, Julio et al. [59] estimated the contribution of 3 energy systems of simulated judo combat. For this, 12 male judo athletes performed 5 combats with different durations (1, 2, 3, 4, and 5 minutes). The method utilized to estimate the energy expenditure during the matches was the same utilized by previous studies [19,21,24]. The results showed that absolute oxidative contribution (70%) was significantly higher when compared to glycolytic (8%) and ATP-PCr absolute contribution (21%). Furthermore, absolute ATP-PCr contribution was significantly higher when compared to glycolytic metabolism. Similarly, the relative oxidative contribution (70%) was significantly higher when compared to relative glycolytic (8%) and ATP-PCr (21%) contributions, whereas relative ATP-PCr contribution was significantly higher in relation to relative glycolytic contribution. These results suggest that oxidative metabolism is predominant to supply the energy cost of judo matches, followed by ATP-PCr and glycolytic contributions. This predominance was observed from the first minute to last minute of combat when compared to the anaerobic systems. In relation to ATP-PCr and glycolytic contributions, the ATP-PCr contribution was higher than the glycolytic from the third minute. However, the ATP-PCr contribution system was reduced as the match duration increased. In other words, during judo combat simulations there is an increase in the oxidative contribution (from 50% to 81%) with a concomitant reduction in the contribution of the ATP-PCr system (from 40% to 12%), while the glycolytic contribution remains relatively constant (between 6% and 10%). These results suggest that oxidative metabolism is predominant, but it is important to emphasize that actions that generate scores and, thus, determine the outcome of the match (i.e. mainly the throwing-technique attacks) require a high rate of energy over a very short period, suggesting they are highly dependent on the ATP-PCr pathway. Furthermore, the glycolytic demand is important during the gripping dispute.

3. Longitudinal studies

Franchini et al. [40] monitored the final phase of preparation of judokas which participated in the 1999 Pan American Games. The athletes were evaluated two and one months before the competition. After the test evaluation, the focus of the training was capacity and power anaerobic during a specific situation of training, along with the technical-tactic training. there was no significant improvement in performance when evaluated through two bouts of upper and lower-body Wingate test and the total number of throws. However, the lactate concentration after the second bout of the Wingate test was lower during the period closer to competition, indicating that athletes performed the same performance with lower glycolytic demand. During the specific training (randori and Special Judo Fitness Test), the lactate concentration was the same in both periods. Although the performance did not change during the specific and no-specific test, the last was performed with a lower glycolytic demand after the training period.

Franchini et al. [62] investigated the effect of three different high-intensity intermittent training (HIIT) during four weeks on the anaerobic performance of 35 judo athletes. Participants were allocated to three groups: 9 athletes in the lower-body HIIT group, 9 athletes in the upper-body HIIT group, 9 athletes in the *uchi-komi* group, and 8 athletes in the control group. The lower-body group performed the HIIT using a lower-body cycle ergometer. These stimuli consisted of two sets of the 20s with 10s interval between sets and 5-min between blocks. Each effort was an all-out bout using 4.5% and 3% of body mass as resistance for the lower-body and upper-body groups, respectively. The upper-body group underwent the same protocol used by the lower-body group, except that the ergometer used was an upper-body bicycle and the load used was 3% of body mass. The specific group was submitted to two blocks of 10 sets of the 20s of the *uchi-komi* (technique entrance) throwing the partner at the end of each set, with 10s intervals between sets and a 5 min interval between blocks. Similar to the other groups, the athletes in this group were also asked to perform every set in an all-out mode. In all groups, the training session lasted for a total of 22 min 40s and athletes performed four lower-body and upper-body Wingate tests before and after four weeks of training. All tests were separated by a 3-min recovery period. Furthermore, blood lactate was measured before each test, 1, 3, and 5-min after the fourth bout. The results showed that the *uchi-komi* group showed a higher upper-body (+16.7%) and lower-body (+8.5%) peak power after the training when compared to before training and the lower-body group increased the mean power (+14.2%) in the fourth lower-body Wingate test. However, there was no significant difference between upper-body HIIT and lower-body HIIT. Thus, different HIIT protocols resulted in upper-body non-specific anaerobic performance improvement in judo athletes.

Additionally, Franchini et al. [63] investigated the effect of low-volume HIIT on performance responses during judo-specific tests. The groups and training protocols were the same as reported in Franchini et al. [63]. Athletes performed a Special Judo Fitness test before and after four weeks of training. The results showed that the upper-body group increased the number of throws after the training (27 ± 2 reps) when compared to values before (25 ± 2 reps), while the lower-body group decreased the HR immediately after the SJFT following four weeks of training (174 ± 9 bpm) when compared to the period before training (181±9 bpm). Furthermore, the *uchi-komi* group reduced the SJFT index after the training (12.07 ± 1.36 beats.min^{-1}.throw^{-1}) when compared to before training (12.84 ± 1.47 beats.min^{-1}.throw^{-1}). Furthermore, the lower-body group decreased the standing sequences number after the training (10 ± 3 times) in comparison to values before training (13 ± 2). Thus, these results showed that all training modes were able to improve judo-specific performance, but each group adapted differently.

Marques et al. [64] investigated the judo-specific performance of state/national level and international judo athletes submitted to block periodization. The sample included 21 elite judo athletes, 11 (5 males and 6 females) were included in the state-national group, and ten (6 males and 4 females) were included in the international group. Block periodization was composed of 13-week training and was divided as follows: five weeks of the accumulation training phase (ACP), followed by a 5-week transmutation phase (TP) and 3-week realization phase (RP). The main physical content developed during the ACP included strength exercises, which were mainly performed using weight training exercises, and conditioning workouts aimed at developing judo-specific strength. During the ACP the technical preparation was mainly throughout *uchi-komi* and *nage-komi* exercises. The main physical training during TP was to develop muscle power. The physical training content included explosive weight training, jumps, and throws, while technical and conditioning workouts were performed according to judo-specific activities, such as *uchi-komi*, and randori. During RP training, the training content for both strength and conditioning, and technical workouts were similar to those developed during TP, but the training volume was substantially reduced and the specific judo technical actions became the main focus of the training program. SJFT test was performed at the beginning of the ACP (T1), after ACP (T2), and after TP (T3). Results showed a higher number of throws at T3 in relation to T1, and T3 when compared to T2. Furthermore, the SJFT index was significantly higher at T1 when compared to T2, and when T2 was compared to T3. Together, these results showed that SJFT performance was sensitive to changes in training content across the block periodization phases and that this approach might be a useful alternative periodization strategy for judo athletes.

Ravier et al. [65] investigated the effects of seven weeks of HIIT on the aerobic and anaerobic metabolism of 17 elite karate athletes. Two groups were studied: 8 athletes in the karate training group (control group) and 9 in the HIIT group (experimental group). The MAOD test was applied before and after 7 weeks of intervention to evaluate the anaerobic capacity. The control group realized their normal karate activity of four to five times per week. The experimental group performed 7-9 sets of a 20s running exercise at an intensity of about 140% of VO2max velocity with a 15s rest between each bout. However, when the athletes could complete more than nine sets of the exercise, running velocity increased by 5%. After the training period, the experimental group increased significantly the MAOD when compared to the values before the training period, but there was no significant difference in relation to the control group. Furthermore, the lactate concentration increased and pH decreased after the supra-maximal test (Table 4).

Table 4: Maximal Accumulated Oxygen Deficit (MAOD, lactate concentration, and blood pH before and after 7 weeks of training in elite karate athletes. Values are expressed as mean ± standard deviation.

Variables	**Training**		**Control**	
	Before	After	Before	After
MAOD (ml·kg)	63.9 ± 6.2	70.5 ± 6.4*	65.5 ± 7.3	62 ± 10
Lactate (mmol·L^{-1})	20.2 ± 2.8	22.8 ± 2.6*	17.9 ± 1.3	18.1± 1.2
pH	7.07± 0.04	6.96 ± 0.05*	7.12 ± 0.04	7.14 ± 0.03

* Significantly difference ($p < 0.05$) when compared to values before the training. (Adapted from Ravier et al. [65]).

The increase in an anaerobic contribution after the HIIT may be due to an increase in glycolytic activity, possibly due to increased activity of phosphofructokinase enzyme [66]. Furthermore, the increase in lactate concentration and a decrease in blood pH after the training indicate an increase in production and/or liberation from the blood to the muscle during the exercise. In contrast, a possible limitation is that both the training protocol and the tests utilized were non-specific to modality. However, is possible to adopt this type of HIIT to the routine of athletes, with specific and actions of the modality as punches and kicks.

Farzard et al. [67] examined the effects of 4 weeks of sprint interval training (SIT) on the anaerobic performance of 15 trained wrestlers. The athletes were divided into two groups: 7 control group and 8 experimental groups. Before and after 4 weeks of training, the athletes performed four bouts of lower-body Wingate test with 4 minutes recovery between each 30s interval to evaluate the anaerobic performance. Furthermore, the lactate concentration was measured at 3, 15, and 30 minutes after the fourth Wingate bout. Both groups followed the same wrestling training sessions, including technique drills, wrestling practice, and strength training for four weeks, 3 sessions per week. Also, both groups had 2 sessions of weight training in the weight room and 1 session of plyometric training. In addition to this training, the experimental group performed a running-based SIT protocol. This protocol was performed in 2 sessions per week and consisted of sets of 6 x 35m sprints at maximum effort with a 10s recovery between each sprint. A set was added in each subsequent week with the same 3 minutes rest between sets. The training program is presented in table 5.

Table 5: Training program for both groups.

Days of week	Control group	Experimental group
Monday	Wrestling training	Wrestling training
Tuesday	Weight training	Weight training
Wednesday	Wrestling training	Wrestling training
Thursday	Weight training	Sprint Interval Training (morning) Weight training (evening)
Friday	Rest	Rest
Saturday	Wrestling training	Wrestling training (morning) Plyometric training (evening)
Sunday	Plyometric training	Sprint Interval Training

The experimental group showed significant improvements in peak power (PP) during the first and second bouts (+ 11% and 12%, respectively) of the Wingate test. Also, the mean power during the first and second Wingate bouts increased significantly (+ 6.1 and 8.9%) in the experimental group when compared with a pre-test.

In resume, the SIT when added to a training routine of karate [65] and wrestlers athletes [67] showed an efficient strategy to improve the anaerobic capacity. Furthermore, this type of intervention with a low volume of training can be implemented in the pre-season and during the season when the purpose of the training was to increase the performance during the short-time period. Although these studies utilized a SIT protocol with non-specific actions of modalities, this training strategy can be utilized with specific techniques of each modality.

4. Non-specific tests to monitor the anaerobic fitness of combat sports athletes

4.1 Wingate test

The Wingate test requires a subject to complete a brief warm-up/lead-in period, pedaling or arm cranking on a stationary ergometer, followed by a 30 s all-out effort at maximal speed against a constant resistance. Peak power is achieved in the first 3 to 5 seconds of this test and thus is dependent on the phosphagens system pathway. Conversely, the power generated during the 30s period is denominated as mean power and related to glycolytic metabolism [69]. Furthermore, the fatigue index is calculated according to Equation 1:

Fatigue Index = (peak power – lower peak power during the test) X 100 / Peak power **(Equation 1)**

The Wingate test results for combat sports athletes are reported in table 6.

Table 6: Wingate results in combat sports athletes. All data are presented as mean ± standard deviation.

Reference	Athletes characteristics	Modality	Load	PP (W)	PP (W/kg)	MP (W)	MP (W/kg)
[22]	Italian Men (3) Female (3)	Karate kumite	7.5 % of BM	NR	 9.1 ± 1.1 9.7 ± 0.6	NR	 7.9 ± 0.6 7.8 ± 0.2
[53]	Czech Men (5) Female (3)	Taekwondo	6% of BM	NR	 14. 7 ± 1.3 10.1 ± 1.2	NR	NR
[69]	Korean Men	Wrestling		NR	11.2 ± 1.8	NR	6.7 ± 1.0
[70]	Brazilian Elite (34) Non-elite (56	Judo		468 ± 63 394 ± 53	5.7 ± 0.8 5.4 ± 0.8	623 ± 80 493 ± 92	7.6 ± 1.0 7.0 ± 1.3

NR: no reported; UB: upper-body; PP: absolute (W) and relative (W/kg) peak power; absolute (W) and relative (W/kg) power.

Recently, Franchini [71] developed a normative classificatory table for upper-body Wingate test performance for judo athletes from different weight categories (Table 7). This normative classificatory table created may be useful as a reference in judo athletes' anaerobic evaluation.

Table 7: Absolute and relative peak and mean power classificatory table in adult judo athletes (n = 179).

	Peak power		Mean power	
	Absolute (W)	Relative (W/kg)	Absolute (W)	Relative (W/kg)
Excellent	>950	>11.41	>620	>7.71
Good	765-950	9.46-11.41	551-620	6.71-7.71
Regular	486-764	6.56-9.45	362-550	4.87-6.70
Poor	377-485	5.42-6.55	298-361	4.33-4.86
Very poor	<377	<5.42	<298	<4.33

5. Specific tests to monitoring the anaerobic fitness of combat sports athletes

5.1 Special Judo Fitness Test (SJFT)

SJFT is divided into three periods (A = 15 s; B and C = 30 s) with 10 s intervals between them. Each partner was positioned 6 m apart and the athlete being tested was required to run to each partner and then throw them as many times as possible using the *ippon-seoi-nage* technique. Both partners had a similar height and body mass as the athlete performing the test. The total number of throws completed is summed; Just after and 1-min after the test, HR is measured. The SJFT index was calculated according to the following equation:

Index = (HR after + HR 1minute after)/total number of throws. **(Equation 2).**

The Intraclass Coefficient of Correlation (ICC) for the total number of throws (0.73), HR after the test (0.93), HR 1 minute after the test (0.89), and index (0.89) is high (1). Furthermore, the index showed a significant correlation with total work performed in the Wingate test (r = 0.71), while the total number of throws presented a significant correlation with relative total work performed in the Wingate test (r = 0.71), fatigue index (r = -0.52) and velocity associated at anaerobic threshold (r = 0.67). The SJFT has a classificatory table based on variables measured during the test (the index, HR immediately and 1 minute after the test, the total number of throws) [72] (Table 8).

Table 8: Classificatory table for the total number of throws, heart rate (after and 1 minute), and index in the Special Judo Fitness Test (Adapted from Franchini et al. [72]).

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

5.2 Frequency Speed of Kick Test (FSKT)

The FSKT has a duration of 10s and during its execution, each athlete is placed in front of the stand bag equipped with a simple trunk taekwondo protector. After a command, the athletes perform the maximal number of kick possible, alternating right and left legs. The turning kick, known as *bandal-tchagui* is using during the test. Performance is determined by the total number of kicks during the test. FSKT was developing by Villani et al. [73]. The reliability of this test was reported as ranging from r = 0.71 to 1 (92) and from 0.82 to 0.86 [74]. Moreover, the FSKT can discriminate female taekwondo athletes, with international/national realizing a higher total number of (91 kicks) kicks when compared to state and regional levels (86 kicks) athletes [75].

5.3 Taekwondo anaerobic test (TAT)

Recently, Sant'Ana et al. [76] propose a method for evaluation of the anaerobic power and capacity of taekwondo athletes. The test consists of kicking a punching bag as many times as possible at maximal intensity over the 30s. The test duration was based on the Wingate test. The athletes start the protocol with their dominant leg, alternating with the kicking leg. The test is performed in a 2 x 2 area, and the kicks (Bandal-Tchagui) had to reach the punching bag at a height between the umbilical scar and xiphoid process. In this test is possible to calculate the number of kicking cycles, mean kicking time, and best kicking time. Furthermore, is possible to identify the magnitude of the impact in each kick in the bi-lateral axis through the highest kicking impact and mean kicking impact over the 30s of the test. In the end, the authors proposed the fatigue index calculated using the mean kicking time and mean the impact of initial 20% cycles and the mean of the last 20% cycles, according to the equations:

Fatigue index by time = (LC – IC)/IC) *100. (Equation 3).

Fatigue index by impact = (IC – LC)/IC) *100. (Equation 4).

Where: LC: mean kicking time/impact on the last 20% of cycles; IC: mean kicking time/impact on the initial 20% of cycles.

The results of the test demonstrated that the number of kicking cycles and mean kicking impact can be considered as indicators of the anaerobic capacity of taekwondo athletes. Furthermore, the best kicking time represents the anaerobic lactic power.

6. Strategies for developing the anaerobic fitness of combat sports athletes

Combat sports are classified as high-intensity intermittent activities with a predominance of aerobic metabolism. However, anaerobic metabolism is important for high-intensity actions during the combats. Therefore, considering the principle of training specificity, the training prescription should be based on the temporal characteristics and the energy contribution of each modality. The effect of high-intensity intermittent training (HIIT) on performance has been related in the literature

[19,77]. By definition, the HIIT involves repeated short to long bouts of rather high intensity interspersed with recovery periods [78]. Recently, the use of sprints and all-out exercises have appeared in the literature [79]. These types of HIIT include Repeated-Sprint Training (RST: sprints lasting from 3 to 7s, interspersed with recovery period lasting generally less than 60s) [79] or Sprint Interval Training (SIT: 30s all-out efforts interspersed with 2-4 minutes of passive recovery period) [77] (Figure 14). Although these training strategies have been utilized during running and cycling activities [78,80], the HIIT can be an effective strategy to improve the physical fitness of combat sports athletes.

Buchheit and Laursen [77] reported several physiological responses desired during a session of HIIT. For example, (1) metabolic, but eliciting essentially large requirements from the O2 transport and utilization systems, i.e. cardiopulmonary system and oxidative muscle fibers; (2) metabolic but with a certain degree of neuromuscular strain; (3) metabolic but with a large anaerobic glycolytic energy contribution; (4) metabolic plus a certain degree of neuromuscular load; (5) metabolic with essentially an important anaerobic glycolytic energy contribution and a large neuromuscular load; (6) eliciting a high predominant neuromuscular strain.

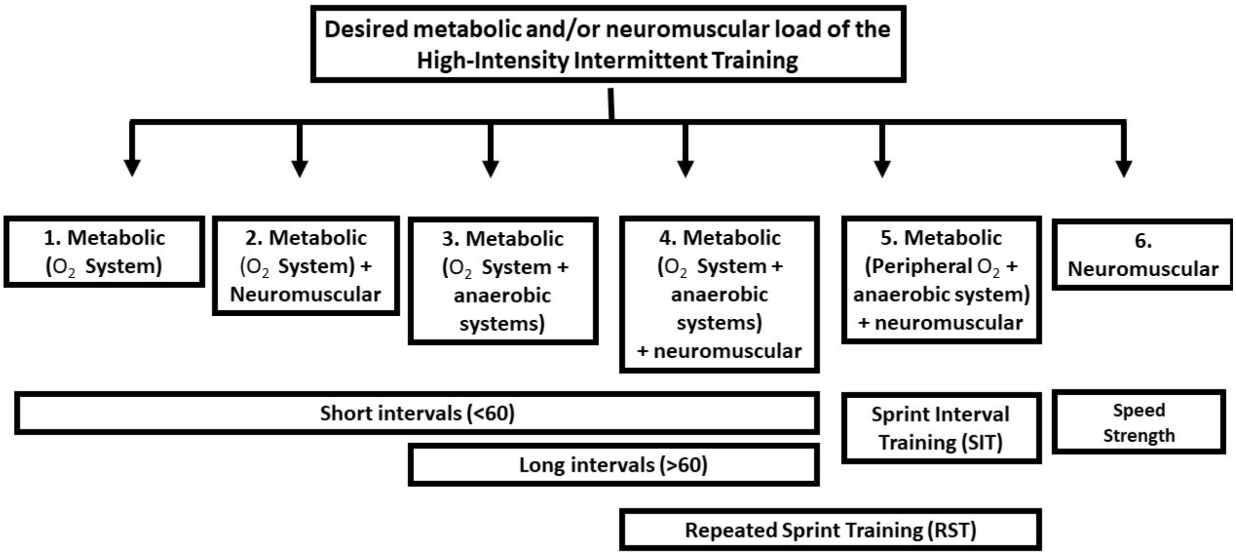


Figure 17: Decision process for selection high-intensity intermittent training (HIIT) based on expected acute physiological responses (adapted from Buchheit and Laursen et al. [77].

Although there are several approaches that, considered in isolation, will achieve a similar metabolic and/or neuromuscular training adaptation outcome, the ability of the coach to understand the isolated acute responses to various HIIT formats may assist with the selection of the most appropriate HIIT session to apply, at the right place and time during the training process. Furthermore, at least nine variables can be manipulated to prescribe the different HIIT session.

The intensity and duration of work and relief intervals are the key influencing factors. In relation to the intensity of effort, Buchheit and Laursen [77] described the variation of intensity according to the objective of HIIT session based on speeds associated with VO2max (vVO2max) or maximal sprinting speed (MSS). For example, during sprint interval training, the intensity of exercise should be corresponding to 180% of vVO2max or intensity corresponding to 95% of MSS. On the other hand, during repeated sprint training the intensity can be between 160-140% of vVO2max or 50-75% of MSS. Although the intensity of exercise is defined through incremental protocols using a treadmill or cycle-ergometer, in combat sports the intensity of exercise can be adapted utilizing specific techniques. For example, judo athletes can be utilized a higher number of throws while taekwondo athletes can utilize a higher number of kicks during a time interval. Furthermore, Buchheit and Laursen [19] related that the manipulation of both duration of exercise and intensity/duration of recovery may substantially impact the glycolytic contribution during the exercise. In activities of 4, intercepted with activities interval lower than the 20s, the lactate concentration after the exercise is consistently higher > 10 mmol·L^{-1}. After that, the number of intervals, the number of bouts, the intensity, and duration between each bout determine the total work performed.

Therefore, the training for combat sports athletes can be directed in a manner to 1) induce responses of lactate concentration in specific activities of the modality similar to those to observe during competitions, as combat simulations with effort:pause ratio similar to those observed during real competitions; 2) adopt supra-maximal intensities, assuming a linear relationship between workload and physiological demand; 3) adopt a series of exercise in which athletes perform the greatest possible effort in a fixed period of time, with intervals for recovery that consider the resynthesis of some energetic substrates or removal of metabolites from anaerobic pathways; 4) adopt the execution of intermittent exercise with intensity, effort, and pause duration similar that occur during a competition [52].

The training stimulus needs to simulate the physiological demand of modality, in this case, the glycolytic demand, that occurs in real conditions of competitions. In this sense, the judo' coaches can perform a short series of *uchi-komi* at the higher intensity possible with short recovery intervals. For example, the protocol utilized by Franchini et al. [62] which utilized different temporal structure (18 x 10s/10s of recovery, 9 x 20s/20s of recovery and 6 x 30s/30s of recovery), but with the same effort: pause ratio. In other words, the number of bouts can vary, but the time of effort of each bout should be the same as the time of recovery. Furthermore, the total time of activity can be based on the duration of combat, 5 minutes for men, and 4 minutes for women.

The taekwondo combats show an effort: ratio around 1:7 to 1:9, with approximately 7-10 attacks per round. Thus, the coach can realize a specific training session of HIIT accordingly to the time-motion that occurs during real combat. For example, execution of specific techniques in the higher intensity possible with a short-term period (1-2s) intercepted with rest intervals (~7s) during 7-10 times. This dynamic can be executed in 3 blocks of 2 minutes, intercepted by a recovery period of 1 minute between each block to simulate the total time of taekwondo combat.

Karate combats show an effort: ratio of 1:10 demonstrating intermittent characteristics. Furthermore, the combat time represents 6% of the total time of combat and the high-intensity actions have a duration of 2s. Therefore, the karate training sessions can adopt this period of time as a reference, subjecting athletes to short high-intensity actions, intercalated with a period of low intensity 10 times repeated over the total time of combat.

HIIT circuit training can be an interesting strategy, in this case, athletes will go through stations, performing the exercise without rest periods. This type of training can be realized based on effort: pause ration and should be applied during the competitive period 3-5 weeks before the principal competition. In relation to circuit training, Del Vecchio et al. [13] described a proposal of training based on this method, for example, two segments of low-intensity standing effort for 9s. After this would be a 10s of passive rest interval followed by three segments of low-intensity groundwork with technical displacement for the 20s, followed by high-intensity groundwork combat ("ground and pound") for 15s, and a 10s passive rest or low-intensity groundwork technical displacements for 20s.

Based on the training circuit proposed by Del Vecchio et al. [13], Shick et al. [81] described an example of circuit HIIT intermittent training in which the training is based on specific actions and effort:pause of MMA. For example, the athletes can shadow box for 1 minute, kick the heavy bag for the 30s, do takedown drills with a partner for 1 minute, perform a shrimping drill for 30 seconds, and finish with guard passing drills for another. The fighter will then rest for 1 minute before starting the circuit again because of a rest period in between sets reflect the duration used in a real fight.

7. Final considerations

Several studies have been demonstrated that combat sports are high-intensity intermittent activities in which the glycolytic demand is high, as inferred by the lactate concentration presented in these studies. However, high lactate concentration did not represent a predominance of glycolytic contribution. On the other hand, other studies demonstrated that when the delta values are analyzed, the glycolytic contribution decreased during the combats or rounds. Furthermore, studies analyzed the energy system contribution of these modalities and demonstrated a predominance of oxidative metabolism, although the decisive actions are determined by anaerobic metabolism. Thus, there is a need to develop the anaerobic fitness of fighters. In this case, the execution of specific actions that consider the effort:pause ratio of each modality can be an efficient strategy to improve the anaerobic fitness of fighters.

Conflict of interest

None declare.

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CHAPTER 3
Developing maximal strength for combat sports athletes

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Abstract
This chapter deals with historical aspects of strength training, contextualizing the relevance of strength training for combat sports to maximize the performance of grapplers, strikers, and mixed martial artists. Scientific articles were listed that presented data related to maximum strength in the leading research databases. Scientific evidence presented in official and simulated matches, and official competitions are presented. Likewise, longitudinal studies on the development of maximal strength in combat sports athletes, maximal strength tests for combat sports athletes (dynamic, isometric, and isokinetic tests), and reference for maximal strength (dynamic and isometric exercises) values in several exercises, as well as normative tables are presented. Another point approached was training prescription for muscle hypertrophy and maximal strength development (dynamic and isometric) for combat sports athletes.

Keywords: Martial arts; combat sports; training; performance; specific tests; muscle strength; strength training; weightlifting.

1. Introduction

From ancient Greece, records have described strength training for athletes' physical preparation [1]. The story suggests that the legendary Milo of Croton, a one-time boys' champion and five-time adult champion of the ancient Olympic Games, carried a calf on his back during his physical preparation. As the animal grew, he continued to carry it by the stadium's distance in Olympia (approximately 212 m) [1,2]. Considering this information and eliminating the exaggerations of this story, one can presume that this is one of the earliest descriptions of the principle of progressive overload or training with increasing loads. Thus, one of the most pursued goals is to reach peak physical fitness in the main competitions. In this context, strength training has been used to maximize athletes' performance in various sports modalities [3]. Table 1 presents data from combat sports athletes who assigned part of their physical preparation to strength training.

Maximal strength is described in the literature as the highest tension that an athlete can perform during a maximal contraction and may be expressed in absolute or relative values [10]. The absolute maximal strength does not consider the body mass of the individual. In contrast, the relative strength is significant in combat sports because athletes are divided into categories according to their body masses [11].

During a match, the power requirement, e.g., entry of a throwing technique by a judo athlete [12] or a kick by a taekwondo/karate athlete [13], and muscular endurance (grip dispute in jiu-jitsu [14] and judo [15] and stepping [16] are common. Nevertheless, the manifestations of maximal strength appear to a lesser extent in the matches, e.g., jiu-jitsu or judo athlete being immobilized pushes the opponent to escape from a position or during the match when an athlete is lying down on

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the groundwork combat, and the opponent needs to project him/her backward on the ground to receive the score [17].

Table 1: Report of athletes who used strength training during their respective physical preparations for competitions.

Athlete	Modality	Titles	Reference
Masahiko Kimura	Judo, jiu-jitsu, and MMA	Various titles	Kimura [4]
Marco Antônio Barbosa	Judo and Brazilian jiu-jitsu	4x Brazilian judo champion, world jiu-jitsu master champion by CBJJ (weight and absolute)	Barbosa [5]
Tiago Camilo	Judo	World judo champion, bronze at the Beijing Olympics Games, and silver in Sydney Olympic games	BJC [6]
Leandro Guilheiro	Judo	2nd place in the world judo championship and bronze in the Athens and Beijing Olympic Games	BJC [6]
Tarsis Humphreys	Brazilian jiu-jitsu	Champion of the 1st world professional Brazilian jiu-jitsu	Dantas and Coutinho [7]
André Galvão	Brazilian jiu-jitsu, grappling, and MMA	World jiu-jitsu champion, champion in grappling tournaments, and athlete of high-level of MMA	Dantas and Coutinho [7]
Diogo Silva	Taekwondo	Pan-American champion in 2007 and the University games in 2009, 4th place in the 2004 and 2012 Olympic Games	Silva [8]
Douglas Brose	Karate	2x world champion	Loturco et al. [9]

Nevertheless, maximal strength training is a determinant for the other phases of sports training periodization, such as power development and muscular endurance [18]. Strength training produces neural and structural changes in the neuromuscular system [3], and improve maximal strength may occur through increased neural activation. In turn, the muscular hypertrophy will result in an increased cross-sectional area of a muscle [19,20]. In this sense, Tricoli [21] shows a direct and linear relationship between muscle mass size and strength performance, e.g., a larger cross-sectional area results in a greater ability to produce strength. Therefore, we consider that the magnitude of strength is a result of three factors [10], including a) intermuscular coordination, b) intramuscular coordination, and c) the frequency of motor unit firing.

In combat sports, athletes' strength training and hypertrophy should emphasize the muscles related to the movements and techniques performed during the match [11,22]. In this view, Steward [23] reported that American Olympic wrestlers had developed muscles that are unnecessary for match demands, which may have a negative impact on performance because an increase in an athlete's body mass may result in a change in the weight category. A study conducted by Moss et al. [24] showed that 9-week training with loads of 90% of one repetition-maximum (1RM) increased participants' strength by up to 15% without increasing the circumference of the exercised muscle. This training systematization is a considerable tool for the physical trainer who works in combat sports, as an athlete who is at the upper limit of his category can maximize the strength gain without increasing muscle mass [22]. A feature of the grappling combat sports is the maximal handgrip strength. There is a substantial demand for maximal isometric handgrip strength in these modalities, and the maintenance of the grip is an essential factor for success in the immobilizations and submissions [11,25].

Therefore, Kraemer et al. [26] indicate that the maximal isometric handgrip strength tends to decrease during an Olympic wrestling competition. The authors suggest that this training method plays a significant role in the routine of elite wrestlers. Also, the maximal isometric strength is observed in different combat stages, for example, in the initial phase of the immobilizations (judo or jiu-jitsu) and the defense of groundwork combat. The exercises that work the maximal isometric strength do not involve actions that alter the muscle's length. Therefore, there is no joint movement, which is considered static [27]. The maximal isometric strength may be worked with a load greater than the maximal concentric strength of an individual and may be combined with dynamic actions during the training. It is worth noting, as a limitation, that the adaptations generated by isometric training are angle-dependent [27].

During training, questions are often raised regarding which method may be most effective in determining victory or defeat in high-level athletes. In this sense, it is assumed that the physical aspects are decisive for success in addition to the technical-tactical question. However, there is no consensus about which training method is the most effective to maximize high-level athletes' performance in combat sports. Also, information regarding athletes' training referential in their respective modalities is not often described in the scientific literature [28]. Considering these aspects, Franchini and Takito [29] investigated the exercise routine of Olympic level judo athletes, and the results suggested that most athletes performed strength training in their respective physical preparations, which reinforces that strength training has been prescribed by physical trainers and performed by high-level athletes. Besides, the retrospective study conducted by Ball et al. [30], with Australian Olympic taekwondo athletes, stresses that strength training is crucial for the development of power (execution of kicks and punches in striking modalities and throwing techniques in grappling combat sports).

In the opposite sense, in some team sports, such as soccer, physical trainers, including Paco Seirulo of Barcelona and Marcelo Martins (ex - Bayer of Munich), have reported that the preparation and physical evaluation of the players have been conducted qualitatively both in real game situations. The professionals emphasized that the training emphasis is given to movement because it reinforces the principle of specificity in this context [31,32]. Researchers have questioned the transfer of strength gains in generic exercises to specific gestures of sports modalities [33]. Nonetheless, there are different physical capacities in combat sports, such as maximal strength, strength-endurance, muscular power, and complementary work with weights at the gym that may aid athletes' physical preparation. From this perspective, research has indicated that the development of these capacities can distinguish elite and non-elite athletes [12,15]. Although there is a belief that strong athletes are slow, no scientific evidence is associated with this empirical theory disseminated in various media [1]. The theory quoted was spread by the lay public who believed that the muscular horses had great strength to pull things; however, they were considered slow and without agility.

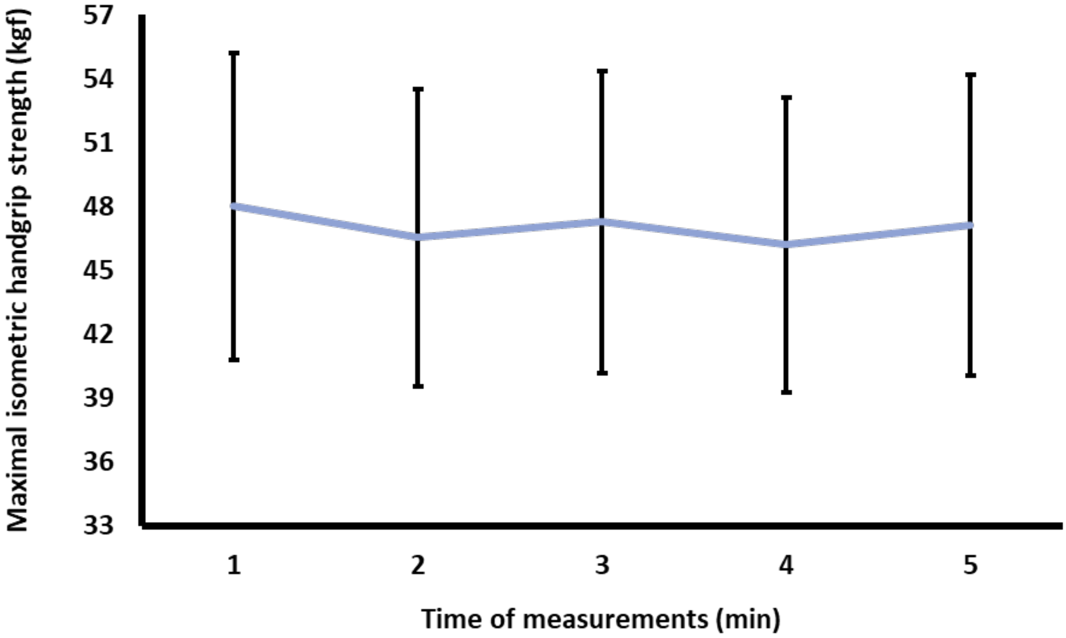
In contrast, Thoroughbred horses were considered famous for having great agility, speed, and muscle power. This thought had a substantial influence at the time (18th century), with diffusion until the present day [1]. However, it is evident that studies involving combat sports are incipient, and there is little information on this topic [34].

In this chapter, the responses of the maximal isometric and dynamic strength are assessed during official competitions, match simulations, and competitions, in response to specific training protocols, tests used to evaluate the maximal strength of combat sports athletes, means and methods for the development of maximal strength and the prescription of maximal strength training for combat sports athletes. In this aspect, the articles are indexed in international research bases, both for the grappling (judo, jiu-jitsu, and wrestling) and the striking modalities (boxing, Muay-Thai, karate, and taekwondo), were prioritized, as well as for mixed martial arts (MMA).

2. Maximal strength responses during grappling combat sports

2.1. Measures conducted during match simulations

To analyze the variation of the maximal isometric handgrip strength during a jiu-jitsu match simulation, Franchini et al. [35] submitted 22 regional level athletes to a 5-min match with breaks 30 s every 1 min. The maximal isometric handgrip strength was measured at the following time points: 1) at rest: 54.2 ± 6.7 kgf for the right hand and 51.4 ± 6.1 kgf for the left hand and 2) during the pauses: 1, 2, 3, 4, and 5 min. Figure 1 presents the maximal isometric handgrip strength values for the different measurement moments (1, 2, 3, 4, and 5 min).



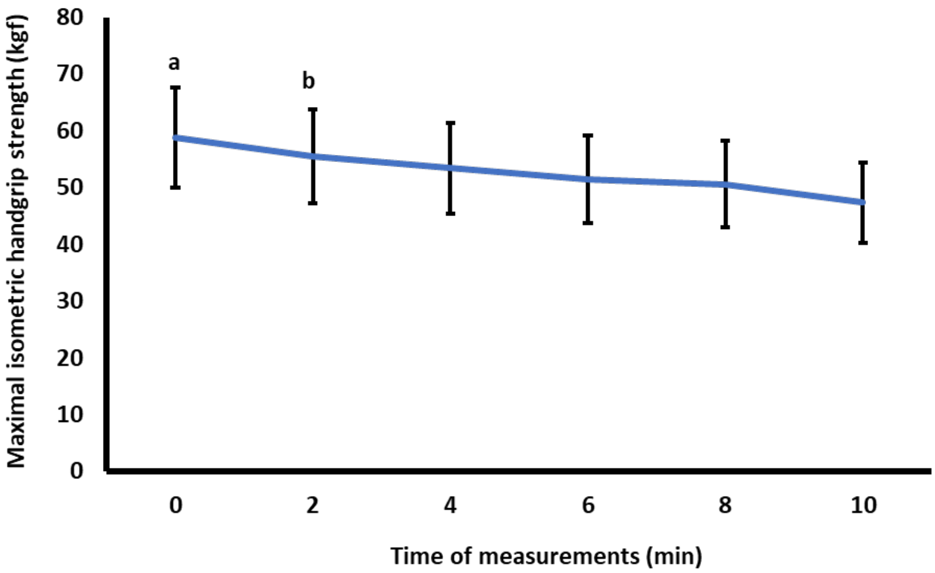
Note: the data represent the mean and standard deviation.

Figure 1: Maximal isometric handgrip strength measured at minutes 1, 2, 3, 4, and 5 (adapted from Franchini et al. [35]).

Regarding figure 1, no differences were found in the measurements made during the match simulations' pauses at different moments of measurement. However, the results showed a decrease of more than 12% of the maximal isometric handgrip strength from the first min of the match against the resting value. Despite this finding, the athletes maintained these values throughout the match, indicating physiological adaptations and/or technical-tactical control. It is valuable to highlight that the authors suggested that the forearm's muscular hypertrophy could maximize the maximal isometric handgrip strength, considering that the forearm circumference positively correlates with the mean maximal isometric strength the match (r = 0.72). Additionally, this study provides the option of predicting the 15 consecutive manual holds (handgrip strength) in a resting situation to monitor muscular endurance during the matches. Also, the mean maximal isometric handgrip strength may be predicted by the mean value of the 15 consecutive contractions since there was a very high correlation (r = 0.93) between these variables and the absence of a difference between the values during the match and the 15 contractions.

Similarly, the authors emphasized that the evaluated jiu-jitsu athletes did not have very high maximal isometric handgrip strength values. However, they were able to maintain this capacity during the whole match. Thus, we note that the pauses of 30 s substantially limit this study's results to perform the measurements every min; that is, the athletes would perform for 1 min, and they would rest for 30 s. Therefore, these pauses may be considered a bias in the recovery of handgrip strength during the match simulation. Nevertheless, the findings of Franchini et al. [35] provide significant answers regarding the isometric handgrip strength because maintaining the handgrip performance is essential for grappling combat sports; the test described (the use of the 15 consecutive contractions) can be a tool easily applied by professionals involved in the physical preparation of these athletes.

Furthermore, the research delineated by Franchini et al. [36] sought to understand the variation of the maximal isometric handgrip strength during jiu-jitsu matches, in which measurements were conducted in the resting condition and every two min with a 30 s pause to perform the measurements. Thus, eight black belt athletes were submitted to a 10 min match simulation (the measurements were performed in the resting condition with the dominant hand at 2, 4, 6, 8, and 10 min). Additionally, the athletes were divided according to their body mass and were instructed to perform the effort identical to that during competition. Figure 2 presents the maximal isometric handgrip strength values for the different measurement moments.

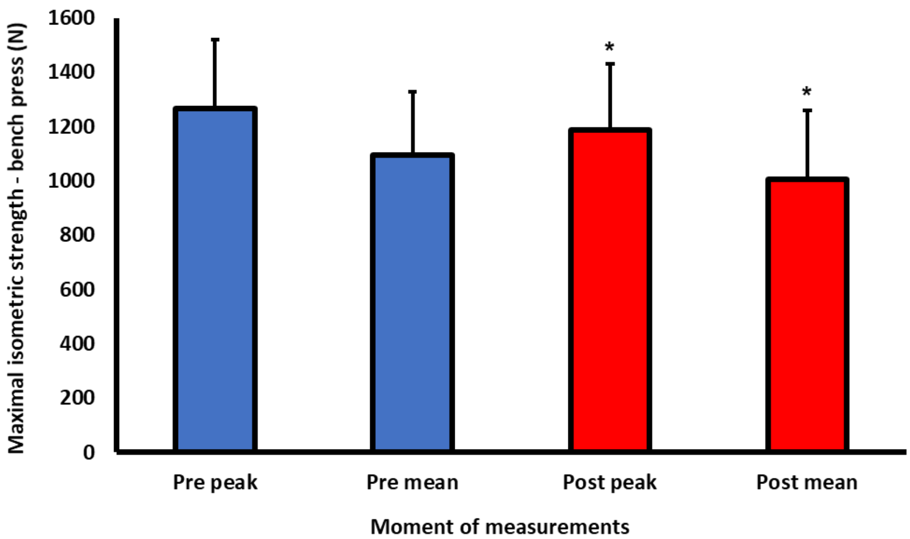


Note: the data represent the mean and standard deviation; a = different (p <0.05) from the values measured in the 4th, 6th, 8th, 10th minutes; b = different (p<0.05) from the value measured at the 10th minute.

Figure 2: Maximal isometric handgrip strength at rest and minutes 2, 4, 6, 8, and 10 (adapted from Franchini et al. [36]).

The results indicated that the maximal isometric handgrip strength presented decreases concerning the moment of rest with sharp declines between the fourth and tenth min. The authors also indicated that the maximal isometric handgrip strength reductions were 20%. The athletes who had less variation reported higher ratings of perceived exertion (RPE) during the match simulation. However, as one potential limitation of this study, one can consider the pauses of 30 s every 2 min since this interval could favor the partial recovery of the handgrip strength in the athletes, which was indicated by the research of Franchini et al. [35].

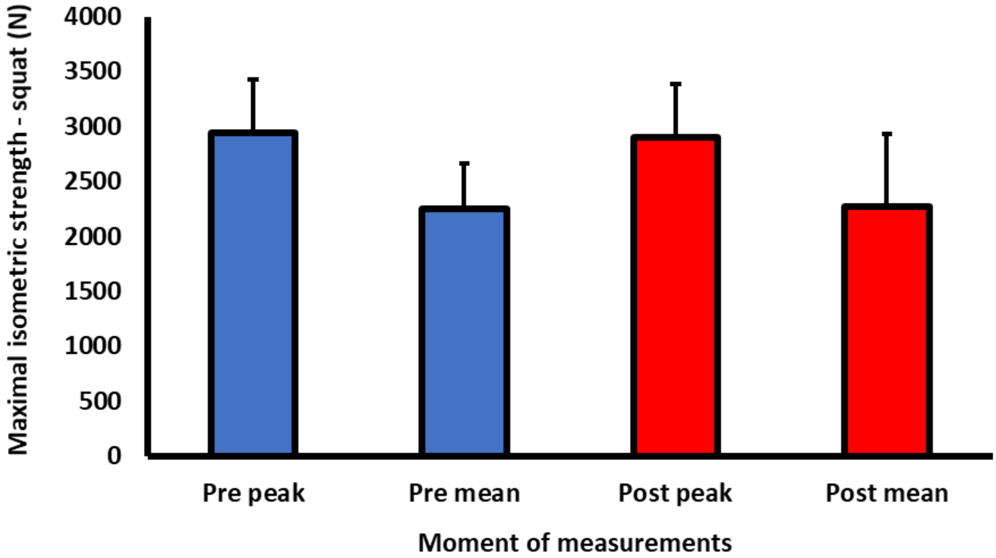
Moreover, the research delineated by Fernandez et al. [37] analyzed the variations of the maximal isometric handgrip strength and maximal isometric strength in the exercises: bench press, squat, and row, before and after a 5 min of match simulation. For this, 8 high-level Spanish athletes were submitted to 10 s of maximal isometric tests on a handgrip dynamometer for both hands and exercises: bench press, squat, and row. For the analysis, a load cell coupled to a bar was used. Figure 3 shows the values of the maximal isometric strength for the bench press before and after the match simulation.



Note: the data represent the mean and standard deviation.

Figure 3: Maximal isometric strength in the bench press: before and after judo match (adapted from Fernandez et al. [37]).

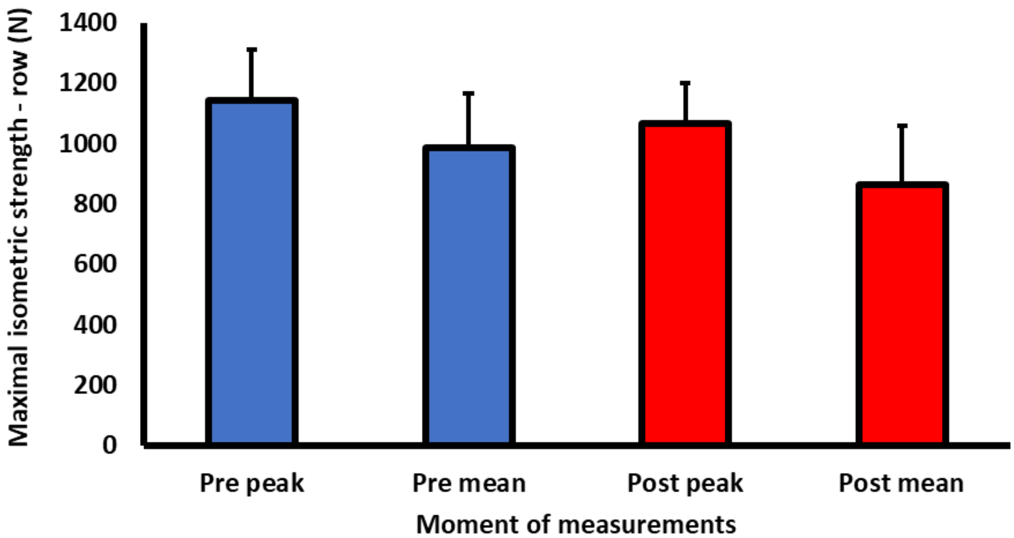
The findings indicated decreases in the maximal peak and mean isometric strength for the bench press with considerably lower values after the match simulation. Figure 4 shows the maximal isometric strength values for the squat exercise before and after the match simulation.



Note: the data represent the mean and standard deviation.

Figure 4: Maximal isometric strength in the squat: before and after judo match (adapted from Fernandez et al. [37]).

For the maximal squat isometric peak and mean strength, no differences were identified for the two measurement moments (pre- and post-match). Figure 5 presents the maximal isometric strength values for the row exercise before and after the match simulation.



Note: the data represent the mean and standard deviation.

Figure 5: Maximal isometric strength in the row: before and after judo match (adapted from Fernandez et al. [37]).

Similarly, no differences in the maximal isometric strength in the row (peak and mean) were identified in the measurements performed before and after the match simulation. Figure 6 presents the maximal isometric handgrip strength values for both hands before and after the match simulation. In the same line, no changes in the maximal isometric handgrip strength were identified for both hands in the measurements made before and after the match simulation. From the results, it may be concluded that the decreases in the peak and mean in the maximal isometric strength in the bench press after the match simulation may be associated with the push actions, which are intended to maintain a safe distance from the opponent. However, the match simulations were not filmed; thus, it is only possible to infer that the significant decreases in the bench press's maximal isometric strength occurred due to these actions. Therefore, research that examines these aspects is necessary. Small improvements were identified for the lower limbs in the countermovement jump after the match simulation, which will be addressed in the muscle power chapter. Nevertheless, this study has submitted the athletes to only a one-match simulation, a situation that does not reflect the demand for an official competition, in which athlete medalists perform between 5 and 7 matches [38,39]. Thus, we indicate that the upper-body muscles' solicitation is very high in judo matches.

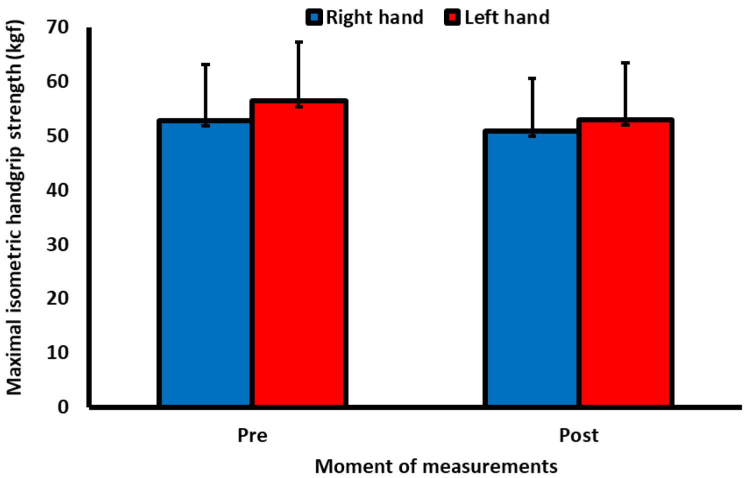


Figure 6: Maximal isometric handgrip strength before and after judo match (adapted from Fernandez et al. [37]).

Note: the data represent the mean and standard deviation.

The research outlined by Bonitch-Góngora et al. [40] investigated the variation of the maximal isometric handgrip strength during simulated judo matches. The objective of that study was to analyze the variations of maximal isometric handgrip strength during simulated judo matches, in which 12 European medalists (10 individuals were medalists in the French and Spanish national championships and two individuals obtained medals in regional competitions in Spain) performed four-match simulations with a duration of 5 min and an interval of 15 min between them. The matches followed the official rules of the competition. However, even with *ippon* (perfect technique), 2 *wazari* (almost perfect technique), joint locks, submission, immobilization techniques, or penalizations, the match was not interrupted because the study needed that the athletes would perform for the same duration. To measure the maximal isometric handgrip strength, the athletes stood with their elbows extended and were instructed to press the dynamometer with the greatest possible strength between 3 and 6 s. The results of the maximal isometric handgrip strength are shown in figure 7.

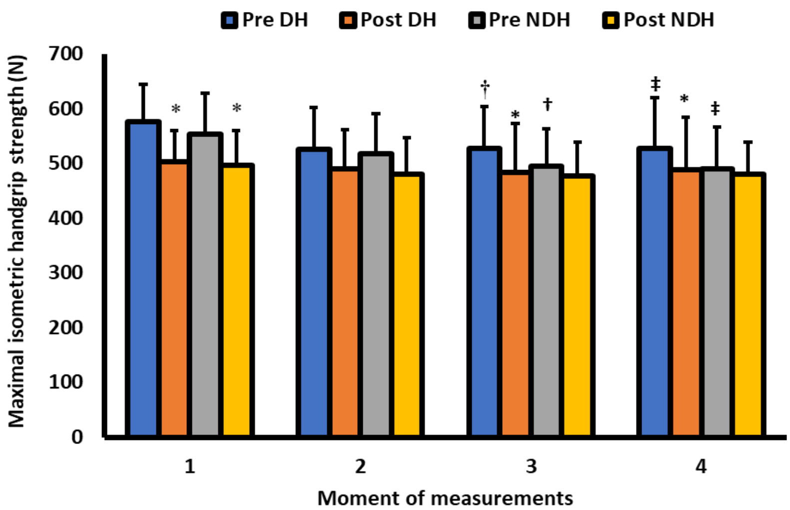
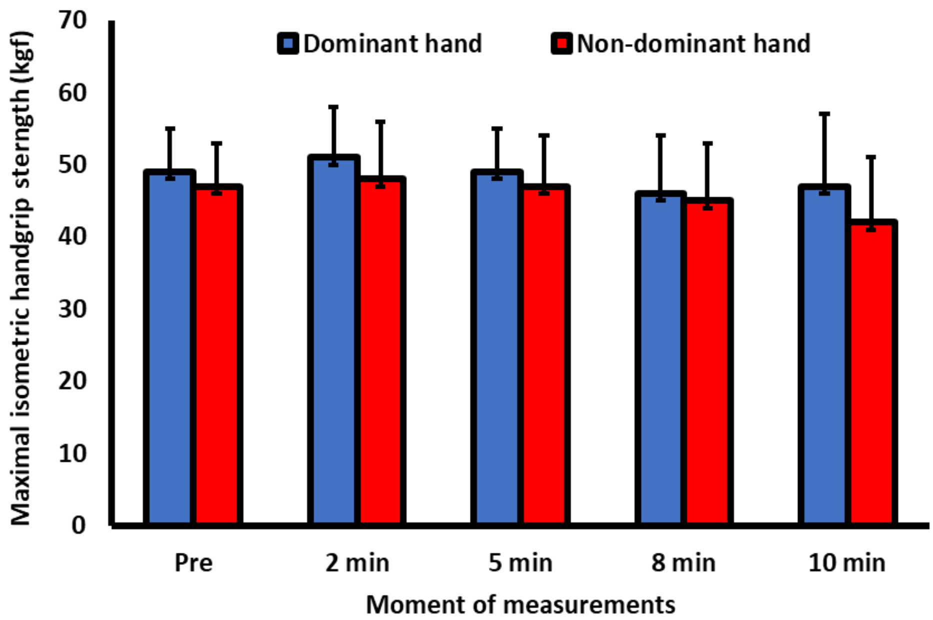


Figure 7: Maximal isometric handgrip strength before and after four judo matches (adapted from Bonitch-Góngora et al. [40]).

Note: the data represent the mean and standard deviation; * = difference ($p<0.05$) between the measurements performed before and after the same match simulations; † = difference ($p<0.05$) between the measurements performed before the first match when compared to the third match for both hands; ‡ = difference ($p<0.05$) between the measurements performed before the first match when compared to the fourth match for both hands; pre = pre-match values; post = post-match values; DH = dominant hand; NDH = non-dominant hand.

As a result of the match simulations, there were decreases in the maximal isometric handgrip strength in the measurements performed before the third and fourth bouts compared to the first evaluation for both hands. However, no differences were found between the dominant and non-dominant hands after the matches. It should also be noted that the findings showed decreases between the measures conducted before and after the first match simulation for both hands. However, differences were identified only for the dominant hand in the measurements obtained before and after the third and fourth match simulations. Moreover, the maximal isometric handgrip strength decreases gradually with the matches' course.

In turn, the study delineated by Andreato et al. [41] aimed to identify the behavior of the handgrip strength of the dominant and non-dominant hands of brown and black-belts jiu-jitsu athletes (n = 10) in match simulations (2, 5, 8, and 10 min). The matches' order with different durations was randomized, and there was approximately 60 min between the other duration matches. Two matches were performed on one day, and two were performed on the following day. The athletes were not informed of the match's total duration, which hypothetically would have a time of 10 min. Even if the end of the match via joint locks or submission occurred, it was not interrupted because the study's purpose was to submit the athletes to the same effort time. Figure 8 shows the values of the athletes' maximal isometric handgrip strength before and after the fragmented matches of 2, 5, 8, and 10 min are presented.



Note: the data represent the mean and standard deviation.

Figure 8: Maximal isometric handgrip strength before and after the jiu-jitsu fragmented match simulations (adapted from Andreato et al. [41]).

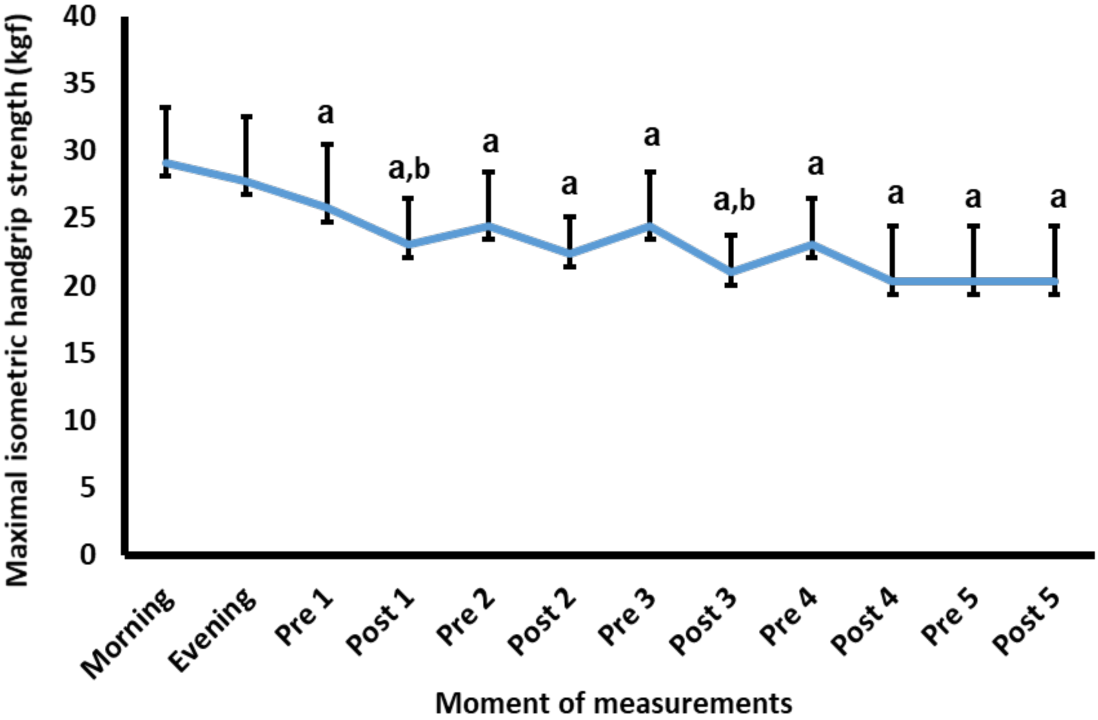
The maximal isometric handgrip strength did not vary because of the fragmented matches (2, 5, 8, and 10 min). These results differed from previous studies with 5-min (Franchini et al. [35] and 10 min (Franchini et al. [36]) jiu-jitsu match simulations. However, the isometric kimono chin-up for the handgrip has decreased. It indicates a gradual reduction of muscular endurance (explored in the section of muscular endurance training).

A similar investigation [42], but conducted with judo, compared the effects of match duration (1, 2, 3, 4, and 5 min) on dominant and non-dominant maximal isometric handgrip strength. They indicated no duration effect on dominant and non-dominant handgrip isometric strength. Still, there was a time point effect on non-dominant handgrip isometric strength, with lower values post- match compared to pre-match. This result can be attributed to the higher strength solicitation of the sleeve hand (non-dominant hand) due to wider movements during the grip dispute in the judo match compared to the lapel grip dispute (conducted with the dominant hand). Additionally, in this study, the tests were applied 6 min after the match, which may provide time to recover some of the maximal strength-related performance variables.

Through the research presented on this topic, it becomes evident that handgrip training should be directed towards maintaining the isometric strength in the forearm muscles, both for the flexor and extensor muscles. Based on the understanding of the muscular and physiological dynamics of *kumi-kata* (handgrip), training can be guided to maintain optimal levels of tension during training and competitions since the muscular demand of the forearm is predominant in grappling combat sports.

2.2. Measures conducted during competition simulations

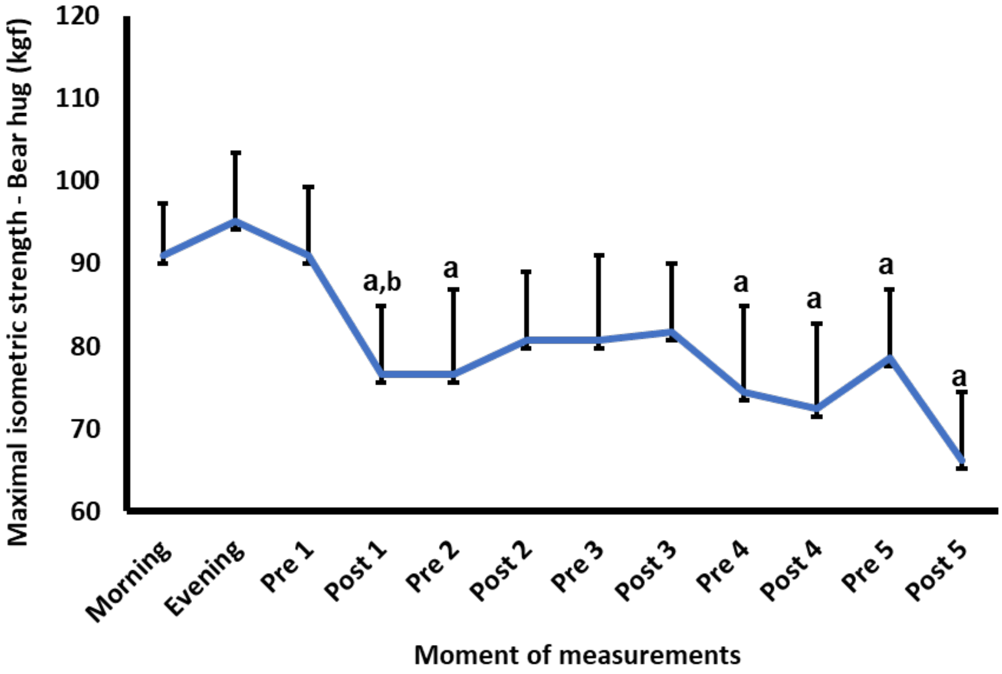
The research conducted by Kraemer et al. [26] aimed to investigate the physiological responses and performance of freestyle Olympic wrestlers (n = 12) during a simulated two-day tournament. Participants were instructed to lose 6% of body mass one week before the competition, a common procedure in which athletes are classified according to their body mass. The weigh-in occurred 12 hours before the first match, and the athletes had to maintain their body mass throughout the competition, with a tolerance of up to 2%. The athletes performed wrestling matches with opponents of similar level and body mass. They performed three matches on the first day of competition and two matches on the second day, each match lasting 5 min. In the morning and afternoon rest periods and before and after each of the five matches, tests were performed for the maximal handgrip strength, bear hug, lumbar traction, and measurement of the isokinetic elbow extension and flexion peak torque. Figure 9 shows the values of the maximal isometric handgrip strength of the athletes in the different moments of measurement indicated.



Note: the data represent the mean and standard deviation; a = different ($p<0.05$) from the value measured in the morning and afternoon at rest conditions; b = different ($p<0.05$) from the value measured before the respective match; morning = measured at rest in the morning and afternoon = measured at rest in the afternoon.

Figure 9: Maximal isometric handgrip strength at rest, before and after 5 Olympic wrestling matches (adapted from Kraemer et al. [26]).

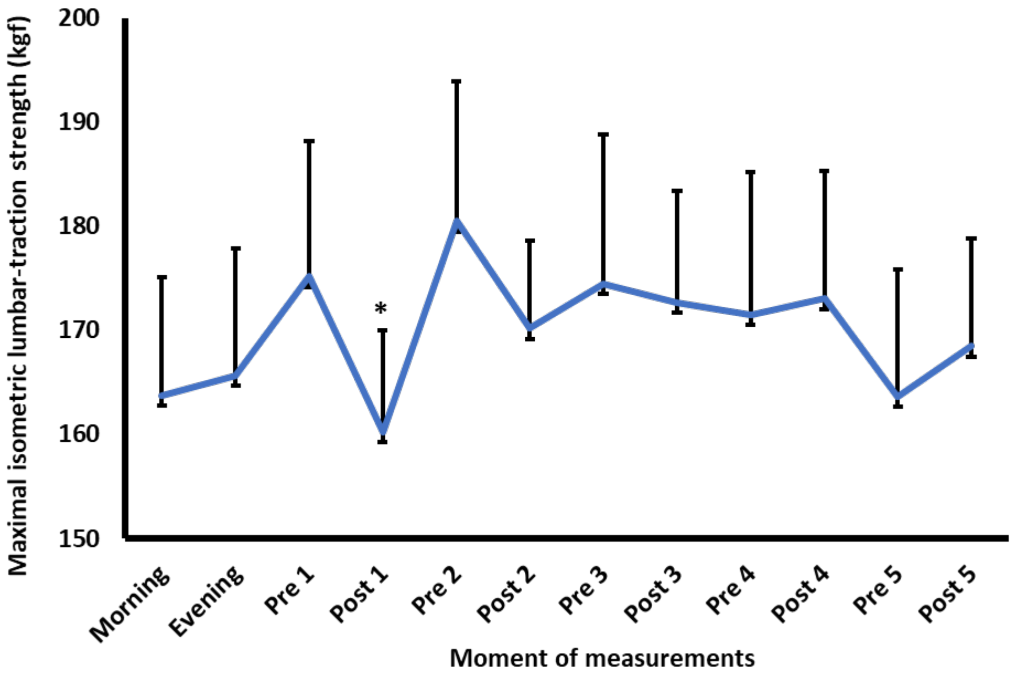
The results showed that the maximal isometric handgrip strength considerably decreased with the pre-match values of the 5 confrontations compared to the rest. Similarly, there were decreases in the maximal isometric handgrip strength when comparing the measurements obtained before and after matches 1 and 3, respectively. These authors indicate that handgrip strength is vital for the Olympic wrestlers and that weight loss may negatively influence athletes' physical performance. Figure 10 shows the values of the maximal isometric strength of the bear hug held by the athletes in the different moments of measurement.



Note: the data represent the mean and standard deviation; a = different ($p<0.05$) from the value measured in the morning and afternoon at rest conditions; b = different ($p<0.05$) from the value measured before the respective match; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 10: Maximal isometric strength in the bear hug at rest, before and after 5 Olympic wrestling matches (adapted from Kraemer et al. [26]).

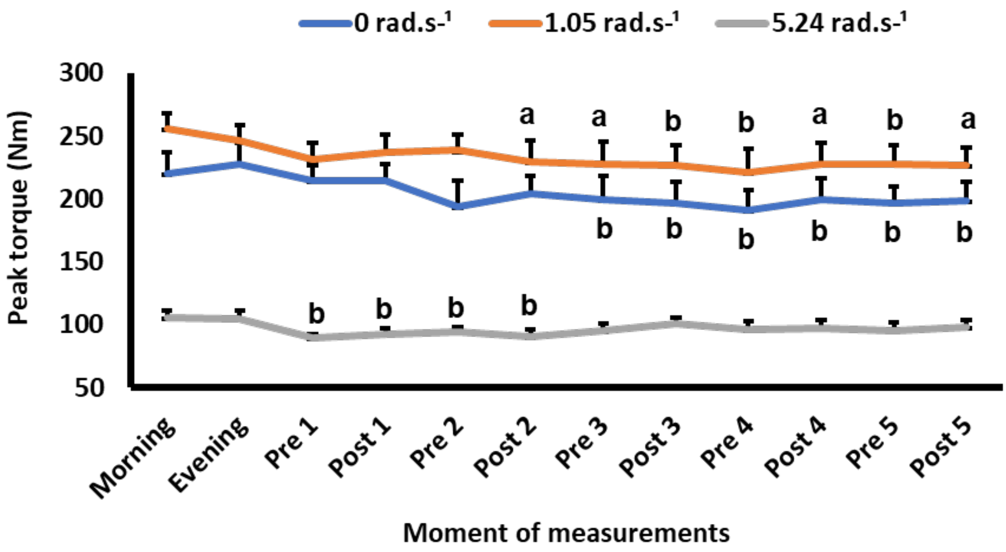
The results show decreases in the measurements performed after match 1 compared to the rest and before the respective match. Besides, there was a decrease in the measurements performed before match 2. Moreover, there were decreases in the measures performed before and after the fourth and fifth matches compared to the rest measurements. Figure 11 shows the athletes' maximal isometric lumbar traction strength at the different measurement moments indicated.



Note: the data represent the mean and standard deviation; * = different ($p<0.05$) from the value measured before the first match; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 11: Maximal isometric strength lumbar traction at rest, before and after 5 Olympic wrestling matches (adapted from Kraemer et al. [26]).

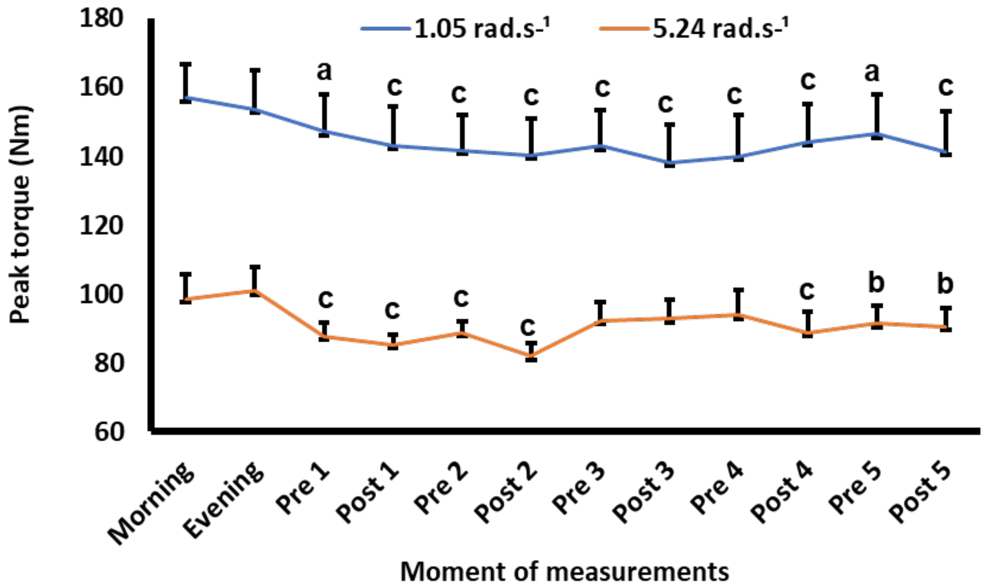
A low value was identified after match 1 concerning that obtained before the same match for the maximal isometric lumbar traction strength. For the other matches, no differences were detected. Figure 12 shows the knee extension peak torque values in the isokinetic test.



Note: the data represent the mean and standard deviation; a = different ($p<0.05$) from the value measured at rest condition in the afternoon; b = different ($p<0.05$) from the value measured at rest in the morning and afternoon periods; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 12: Peak torque for knee extension in isokinetic apparatus with angular velocities of 0, 1.05, and 5.24 rad.s^{-1}, at rest, before and after 5 Olympic wrestling matches (adapted from Kraemer et al. [26]).

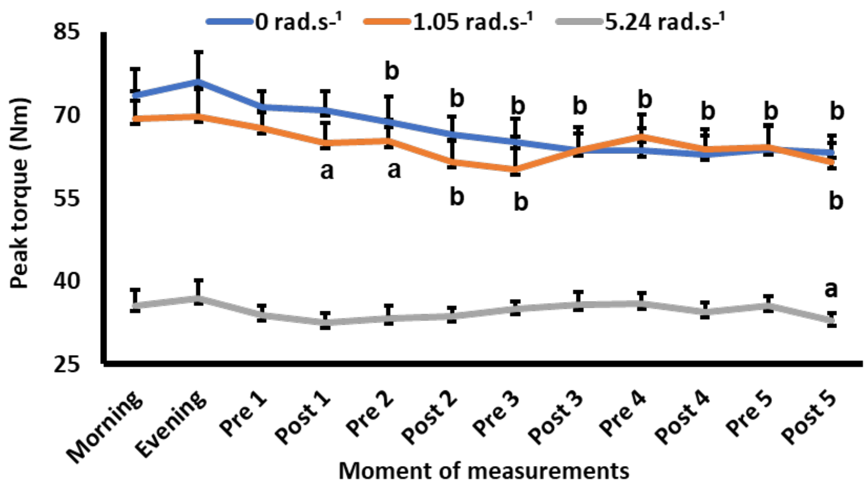
This figure identifies a sharp drop in the maximal peak torque for knee extension at 0 rad.s^{-1} before match 3 and the other subsequent moments to the values measured at rest in the afternoon. Regarding the peak torque at 1.05 rad.s^{-1}, decreases were identified from the pre-match 3 assessment and all subsequent measurements compared to the rest measured values in the two periods. Moreover, for the peak torque at 5.24 rad.s^{-1}, decreases from the first match to the post-match 2 evaluation were identified when the measurements performed at rest in the two periods were compared. Figure 13 shows the peak torque values in the isokinetic test for knee flexion.



Note: the data represent the mean and standard deviation; a = different ($p<0.05$) at rest value measured in the morning; b = different, ($p<0.05$) at rest values measured in the afternoon; c = different ($p<0.05$) from morning and afternoon rest values; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 13: Peak torque for knee flexion in isokinetic apparatus with angular velocities of 0, 1.05, and 5.24 rad.s^{-1}, at rest, before and after 5 Olympic wrestling matches (adapted from Kraemer et al. [26]).

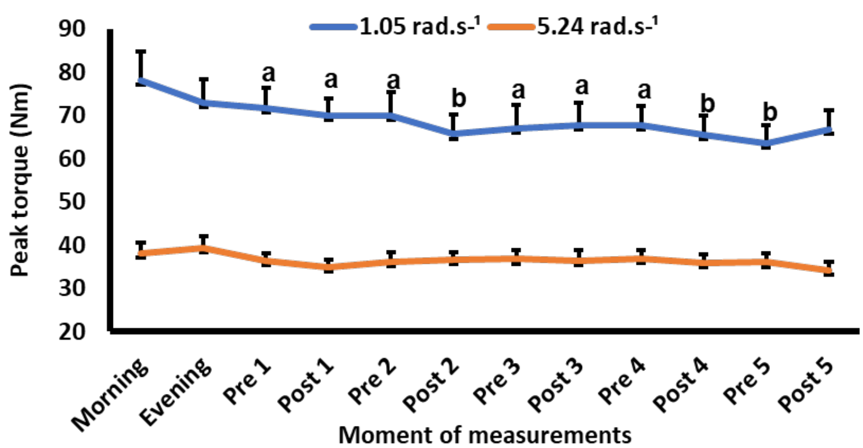
In this figure, there is a decrease in the peak torque for knee flexion at 1.05 rad.s^{-1} before match 1 and before match 5 compared with the measurements performed at rest in the morning. Similarly, there were marked decreases in the peak torque for knee flexion at 1.05 rad.s^{-1} after match 1 until after match 4 and after match 5 concerning the control condition measures in the morning and afternoon. For the peak torque for knee flexion at 5.24 rad^{-1}, decreases were identified before match 1 through the post-match 2 assessment and post-match 4 compared to the measures performed in rest in both periods. Also, there were decreases in the measurements performed before match 5 and after match 5 with the values without previous fatigue (i.e., the control condition in the afternoon). In figure 14, we present the peak torque values in the isokinetic test for elbow flexion.



Note: the data represent the mean and standard deviation; a = different (p<0.05) at rest value measured in the morning; b = different, (p<0.05) at rest values measured in the afternoon; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 14: Peak torque for elbow flexion in isokinetic apparatus with angular velocities of 0, 1.05, and 5.24 rad.s^{-1}, at rest, before and after 5 matches of Olympic wrestling (adapted from Kraemer et al. [26]).

This figure identifies decreases in the peak torque for elbow flexion at 0 rad.s-^{1} after match 2 until the end of the competition's simulation. The values are measured at rest in the two periods. Moreover, decreases in the peak torque for elbow flexion at 1.05 rad.s^{-1} after match 1 and before match 2 are identified compared with the control measures performed in the afternoon. Similarly, there were reductions after match 2, before match 3, and after match 5 compared to the measurements performed at rest in both periods. In turn, for the peak torque for elbow flexion at 5.24 rad.s^{-1}, a decrease was identified only after match 5 about resting values in the afternoon. In figure 15, we present the maximal peak torque values in the isokinetic test for elbow extension.



Note: the data represent the mean and standard deviation; a = different (p<0.05) at rest value measured in the morning; b = different, (p<0.05) at rest values measured in the afternoon; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 15: Peak torque for elbow extension in isokinetic apparatus with angular velocities of 0, 1.05, and 5.24 rad.s^{-1}, at rest, before and after 5 Olympic wrestling matches (adapted from Kraemer et al. [26]).

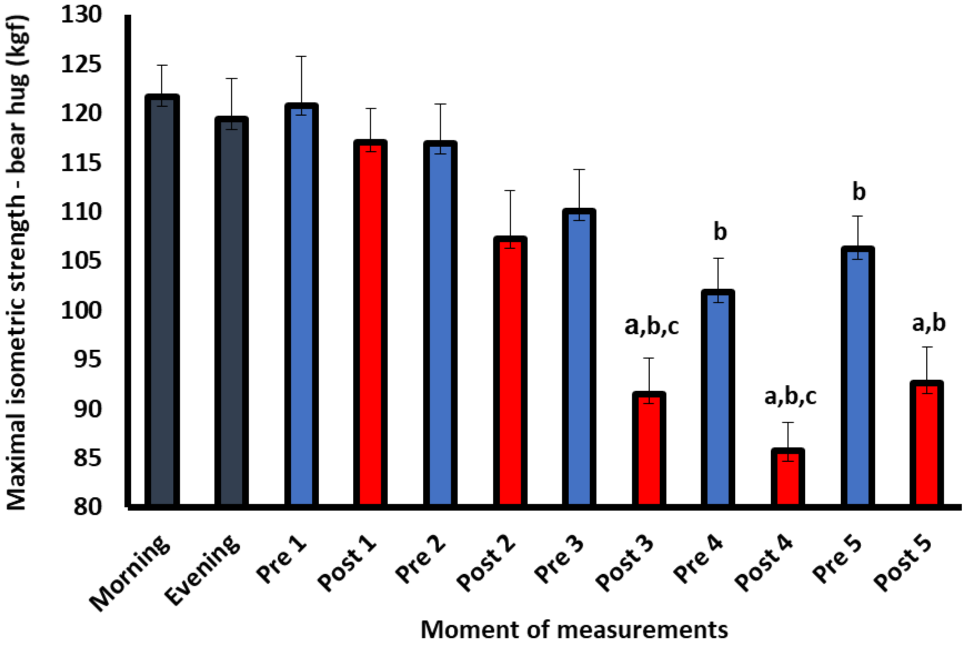
In this figure, it is possible to identify decreases in the peak torque for elbow extension at 1.05 rad.s^{-1} in the measurements obtained before and after match 1, before match 2, before and after match 3, and before match 4 compared with the measurements performed in the rest situation in the morning. Similarly, there were differences in the measures performed after match 2 and 4 and before and after match 5 compared to the rest measures in the two periods. However, no differences were identified for the peak torque for elbow extension at 5.24 rad.s^{-1}.

It is worth mentioning that the isokinetic test evaluates the peak torque of the joint in an isolated and unilateral manner with an isometric angular velocity for 0 rad.s^{-1} and dynamic for 1.05 rad.s^{-1} and 5.24 rad.s^{-1}. In this sense, the athlete would have to expend extra strength to perform the test at a slower speed. Consequently, the tests' results at 1.05 rad.s^{-1} showed marked decreases in the various moments of measurement for flexion and extension of knees and elbows. Isokinetic testing has been used to assess muscle imbalance between right and left sides and between antagonistic muscle groups in specific actions and is usually indicated after injuries or surgeries that keep athletes from training and competition. Although the authors evaluated the peak torque performance using these procedures, the degree of transference of the measurements obtained with certain muscle groups' isolation to more complex actions commonly required in applying techniques during the match is questionable [43–45].

The performance oscillations between the tests performed before and after the match simulations (decrease in performance in the measurements) may be related to the athletes' technical-tactical actions. However, it is impossible to state this hypothesis because a technical-tactical analysis was not performed in this study. It is worth noting that the competition's simulation was carried out in 2 days, with three matches in one day and two matches on the following day. Similarly, elevations in muscle damage markers, such as creatine kinase (CK), were found, especially on the second day of competition, indicating the high damage caused by the three-match simulations on the first day [46,47]. Therefore, the physiological responses showed a limit for the strength generation. Also, there was no complete recovery between the match simulations, which corroborates the decrease in performance in the physical tests during the tests/matches. Besides, it is evident that despite the natural exhaustion of the matches and evaluations performed, the ideal physical preparation and the monitoring of the diet seem to be determinants for maintaining the competitive performance.

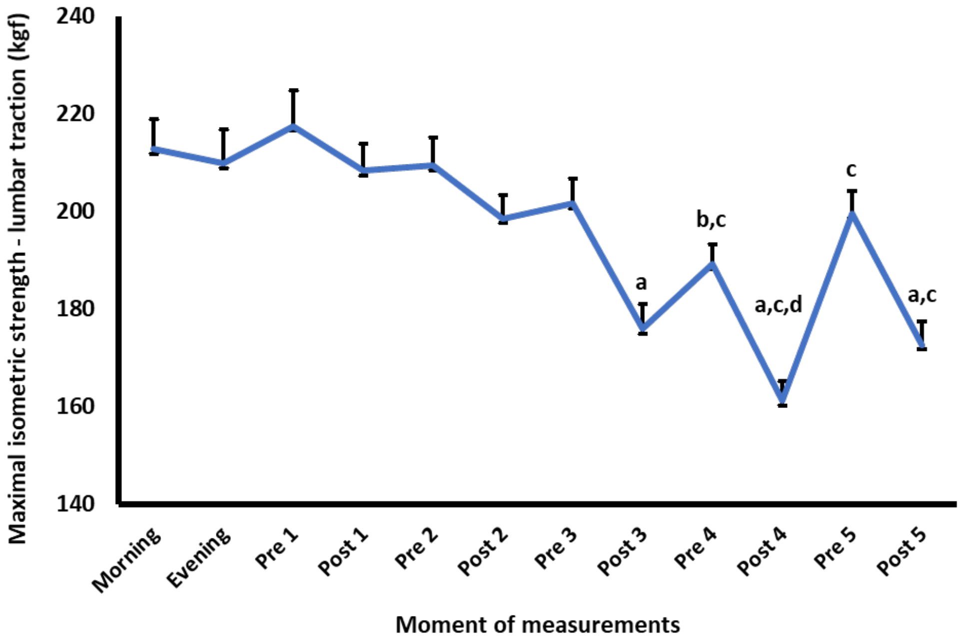
Furthermore, the research conducted by Barbas et al. [48] aimed to evaluate the physiological adaptations and performance of Greco-Roman style matches during a one-day competition simulation. To this end, 12 high-level athletes from the junior category were recruited. They were submitted to 5 three-round matches, 2 min for each round with 30-s intervals between the rounds. Baseline assessments were conducted in the morning and the afternoon one week before the simulated competition. The break from the first match to the second match was 80-90 min, from the second match to the third was 60-70 min, from the third to the fourth was 35-45 min and from the fourth to the fifth was 5-6 hours. The maximal strength tests performed included the bear hug, maximal isometric handgrip strength, and maximal isometric lumbar traction strength. All measurements were performed in the following moments and conditions: 1) rest in the morning and afternoon and 2) before and after the 5 match simulations. In figure 16, we present the variation of the bear hug's maximal isometric strength during the simulated tournament.

For the maximal isometric strength in the bear hug, lower values were found after match 3 compared with the measurements obtained before the respective match, the previous match, and the first match. In the evaluation performed before match 4, decreases were identified compared with the assessments conducted in the first match and the resting situation. About the measurements obtained after match 4, marked reductions were identified compared with the measurements obtained before the respective match and to the first match. Finally, decreases in the measurements performed before match 5 were identified compared to the measurements obtained during the first match and rest. Moreover, the evaluation performed after match 5 showed decreases in the measurements obtained before the respective match and in comparison to the measurements obtained in the first match. Figure 17 shows the athletes' maximal lumbar traction strength at different measurement moments.



Note: the data represent the mean and standard deviation; a = different (p<0.05) between pre and post-match values; b = different (p<0.05) from the value of the first match; c = different (p<0.05) from the previous match; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

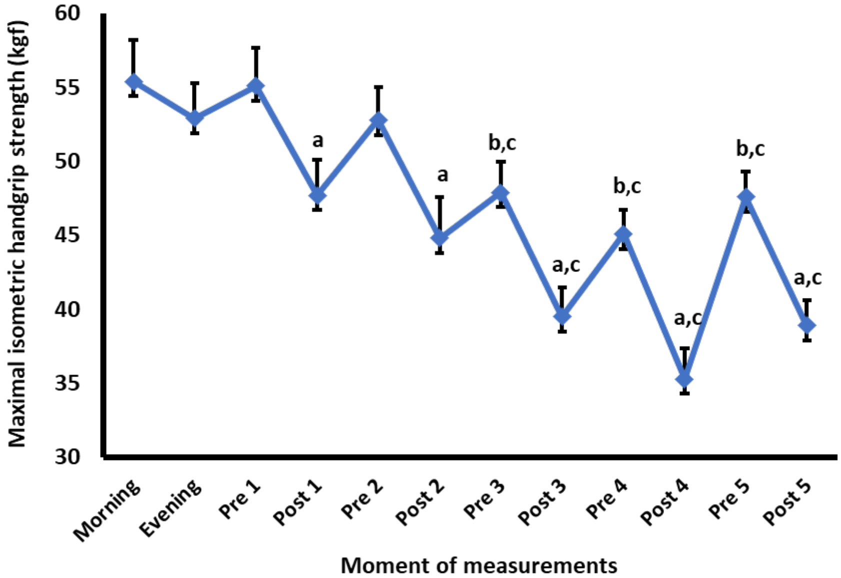
Figure 16: Maximal isometric strength in the bear hug at rest in the morning and afternoon and before and after the five simulated matches (adapted from Barbas et al. [48]).



Note: the data represent the mean and standard deviation; a = different (p<0.05) between pre and post-match values; b = different (p<0.05) from the value of the first match; c = different (p<0.05) from the previous match; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 17: Maximal isometric strength lumbar traction at rest in the morning and afternoon and before and after the five simulated matches (adapted from Barbas et al. [48]).

In this figure, we can identify decreases in the maximal isometric lumbar traction strength after match 3 compared with the measurements obtained before the respective match. Similarly, there were marked decreases in the measurements performed before match 4 compared to the measurements obtained in the first match and the rest situation. Consequently, reductions in the measurements obtained after match 4 were identified in comparison to the values obtained before the respective match, the previous match, and the first match. Also, differences in the measurements obtained before match 5 were verified when compared to the first match measurements. Finally, decreases were identified after match 5 compared to the measurements obtained in the first match and before the respective match. Figure 18 shows the athletes' maximal isometric handgrip strength at different measurement moments.



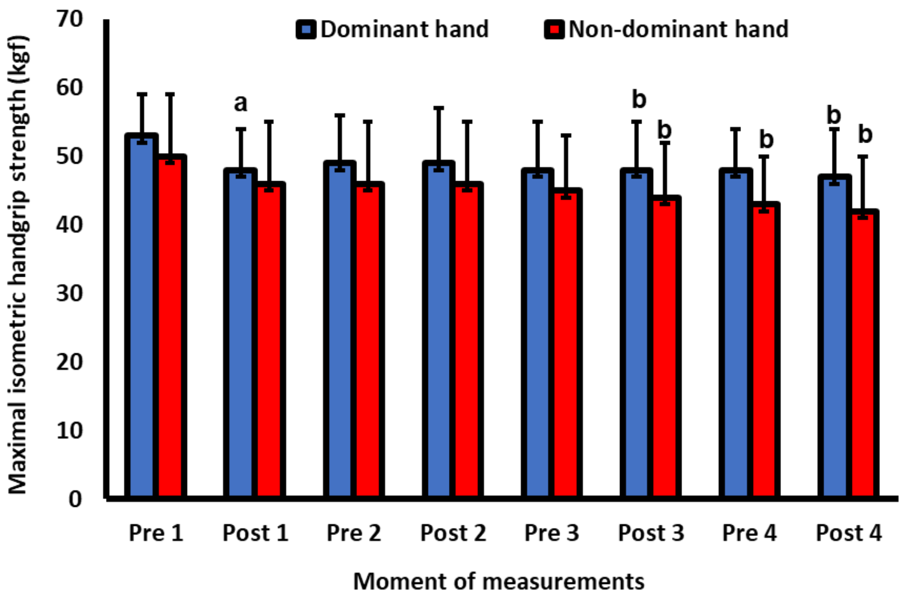
Note: the data represent the mean and standard deviation; a = different (p <0.05) between pre and post-match values; b = different (p<0.05) from the value of the first match; c = different (p<0.05) from the previous match; morning = measured at rest in the morning; afternoon = measured at rest in the afternoon.

Figure 18: Maximal isometric handgrip strength at rest in the morning and afternoon and before and after the five simulated matches (adapted from Barbas et al. [48]).

In this figure, it is possible to identify a decrease in the maximal isometric handgrip strength after matches 1 and 2 compared to the measurements performed before the respective matches. Significant reductions were placed in the evaluations conducted before match 3 compared to the first match measurements and the rest of the two periods. Similarly, differences in the measurements obtained after match 3 were identified compared to the measurements obtained before the same match. Therefore, decreases were found compared to the first match measurements. Regarding the evaluations performed before the 4th match, there were decreases compared to the assessments conducted during the first match and the rest situation in the two periods. After match 4, reductions were observed to the measurements obtained before the respective match compared to the first match measurements.

Similarly, reductions were found in the measurements obtained before match 5 compared to the first match and the two periods' resting condition. Besides, there were reductions in the measurements performed after match 5 compared to the first match and the evaluations conducted before the respective match. The largest decreases were identified after the fourth match, as the rest between the third and fourth matches (between 35 and 45 min) were insufficient for optimum recovery of the athletes. The authors indicated that the performance presented a progressive impairment during the one-day competition, mainly attributed to fatigue, stress, and muscular micro-damage. Finally, the adoption of recovery strategies can be developed to maintain elite wrestlers' performance in competitions.

Additionally, the research delineated by Andreato et al. [49] had among its objectives to identify the behavior of the handgrip strength of the dominant and non-dominant hands of experienced jiu-jitsu (n = 10) athletes (brown and black belt) during a competition simulation, which included 4 simulated matches. The match time was the same as in an official competition for an adult black belt (10 min), with a 20-min interval between the simulations. The matches were not interrupted in finalization cases (submission or joint lock) because the research intended to submit the athletes at the same effort duration. Figure 19 presents the values of the maximal isometric handgrip strength of the study of Andreato et al. [49].



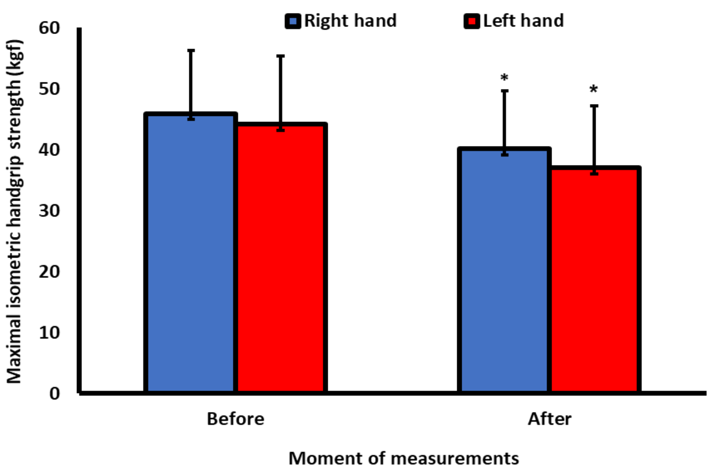
Note: the data represent the mean and standard deviation; a = different (p<0.05) from the measured value before the first match simulation for the dominant hand; b = different (p<0.05) from the measured value before the first match simulation for both sides.

Figure 19: Maximal isometric handgrip strength before and after jiu-jitsu match simulations (adapted from Andreato et al. [49]).

This figure's results indicate decreased values in the maximal isometric handgrip strength in the dominant hand after the first, third, and fourth match simulations. For the non-dominant hand, decreases in the maximal isometric handgrip strength were identified after the third and before and after the fourth match simulations. Nonetheless, there is a decrease in the maximal isometric handgrip strength during the matches. Previous studies have indicated that the forearm strength-endurance seems to be more essential to maintain the handgrip in a jiu-jitsu match [14,35] and judo [15] maximal isometric handgrip strength.

2.3 Measures conducted during official competitions

The research conducted by Andreato et al. [50] had the objective to evaluate the maximal isometric handgrip strength before and after matches in an official jiu-jitsu competition. Thirty-five white to brown-belt athletes from different competitive levels agreed to participate in the study. Figure 20 values the athletes' maximal isometric handgrip strength before and after the matches are presented.

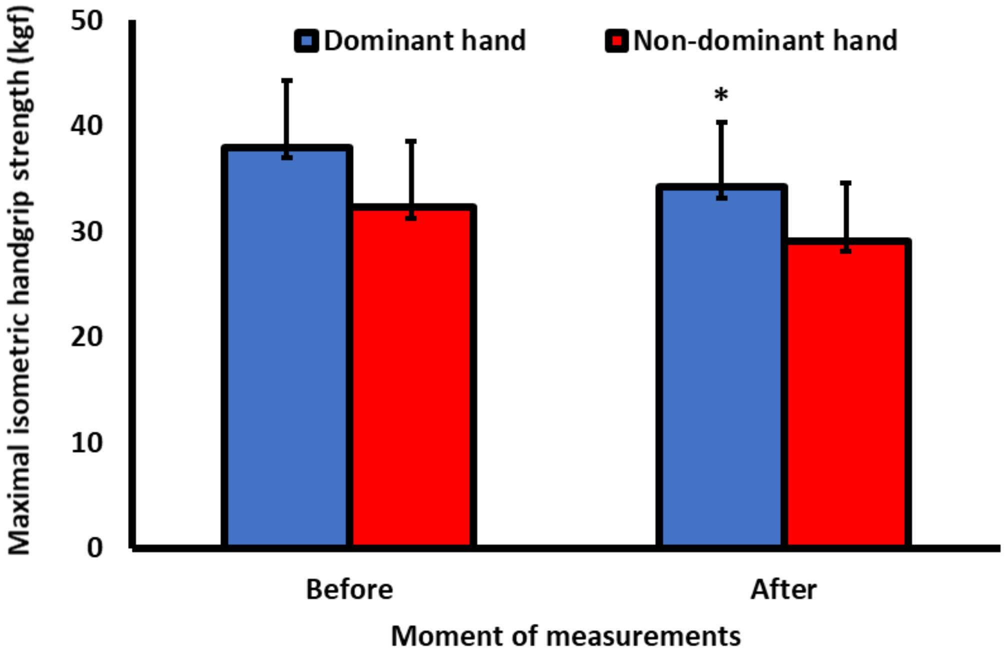


Note: the data represent the mean and standard deviation; * = different (p<0.001) from the measured values before the match.

Figure 20: Maximal isometric handgrip strength before and after jiu-jitsu official match (adapted from Andreato et al. [50]).

There was a decrease in the maximal isometric handgrip strength after official jiu-jitsu matches. The authors emphasized that exercise to handgrip in training sessions, i.e., exercises such as dynamic and isometric chin-ups using the *gi*, may maintain the handgrip during the matches. In the chapter about strength-endurance, specific handgrip and forearm exercises will be performed because of this finding.

Likewise, the study by Andreato et al. [51] had as the objective to assess the maximal isometric handgrip strength of the dominant and non-dominant hands in 12 athletes (three athletes were medalists in national competitions and nine athletes received medals in regional competitions) of jiu-jitsu during an official competition. The athletes were blue-belt with 2.8 ± 1.2 years of systematic training. As an inclusion criterion, athletes with a year and a half of uninterrupted practice of the modality were accepted in the study. For this purpose, measurements of the maximal isometric handgrip strength were performed before and after the official jiu-jitsu matches. In figure 21, the values of the maximal isometric handgrip strength of the athletes before and after the matches are presented.



Note: the data represent the mean and standard deviation; * = different ($p < 0.05$) from the measured values before the match.

Figure 21: Maximal isometric handgrip strength before and after jiu-jitsu official match (adapted from Andreato et al. [51]).

There were significant decreases in the maximal isometric handgrip strength in the dominant hand after the combat than the fight measurements. There was a downward trend for the non-dominant hand. However, no decreases were identified after the official fight. The findings may show that athletes performed more intense actions with the dominant hand; however, this variable was not measured in the study, as mentioned above. The study results indicate that the maximal isometric handgrip strength was maintained at 90% of the resting situation values since the high incidence of forearm fatigue was reflected in the decrease in the maximal isometric handgrip strength.

So far, only one investigation measuring maximal isometric handgrip strength in judo official matches was found [52]. A different number of athletes was assessed along an official competition (post-match 1 = 34 athletes; post-match 2 = 28; post-match 3 = 25; post-match 4 = 9), comparing medalists and non-medalists, and information is provided only for right and left hand, with no details concerning dominant and non-dominant hand or the interval duration between matches. They reported that no difference was found between medalists and non-medalists. In contrast, the maximal isometric right handgrip decreased post-matches 3 and 4 compared to pre-match, post-matches 1 and 2, whereas for the left hand, lower values were observed post-match 3 compared to pre-match, and lower values post-match 3 compared to post-match 2.

3. Maximal isometric strength responses during striking combat sports

Chiodo et al. [53] studied the maximal isometric handgrip strength of 15 Italian high-level taekwondo athletes, including four women and eleven men. The criteria for inclusion in the study were participating in international competitions (European Championships, World Championships, and Olympic Games) and weekly training frequency equal to 6 weekly sessions. On the first day, the maximal isometric handgrip strength at rest (among other measures) was measured. On the second day, the matches were executed during an official competition, consisting of three rounds of 2 min interspersed with 1 min of passive rest. The measures were implemented shortly after the end of the match. Figure 22 shows the values of the athletes' maximal isometric handgrip strength before and after the taekwondo competition. These results indicate differences in the maximal isometric handgrip strength between both male and female athletes. Moreover, there were decreases in the maximal isometric handgrip strength of both males and females after the match. The authors attributed the reduction of the maximal isometric handgrip strength (8% of reduction) to hand-to-hand contact, protection of opponents' kicks, and punches' execution. However, the use of the handgrip test does not seem to be specific to evaluate the upper-body actions and specifically the wrists and forearm solicitation during the combat, as the use of the lower-body is predominant in the taekwondo match, with 98% of the actions executed by these muscular groups [13]. The match's activities did not involve grappling moves, except for the wrists' closing to maintain the guard and prepare eventual punches.

Therefore, Tassiopoulos and Nikolaidis [54] sought to identify the maximal isometric handgrip strength's acute effect during an official national level kickboxing in winners and losers. The combats were composed of three rounds of 2 min interspersed by 1 min of passive rest. Thirty-one Greek athletes with 4.8 ± 3.1 years of practice of the modality participated in the study. The maximal isometric handgrip strength was measured in two moments: before and after the official kickboxing matches. Figure 23 shows the maximal isometric handgrip strength values before and after the official kickboxing matches.

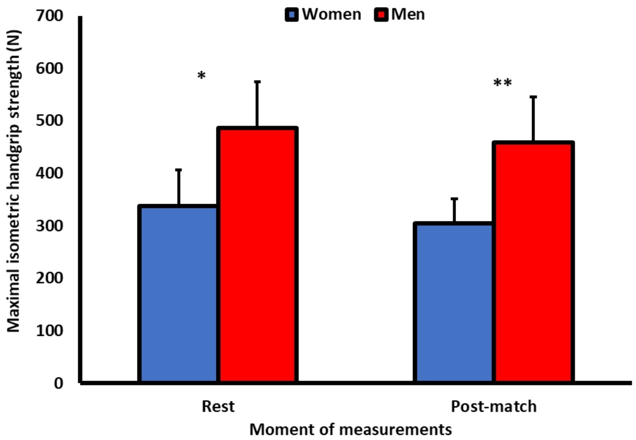


Figure 22: Maximal isometric handgrip strength at rest, before and after a taekwondo official match (adapted from Chiodo et al. [53]).

Note: the data represent the mean and standard deviation; * = difference between the sexes (p<0.001); ** = difference of measurements performed at rest condition (p<0.01).

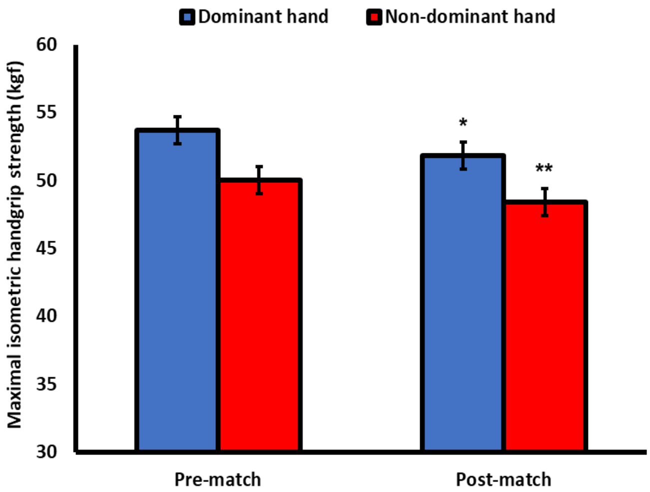
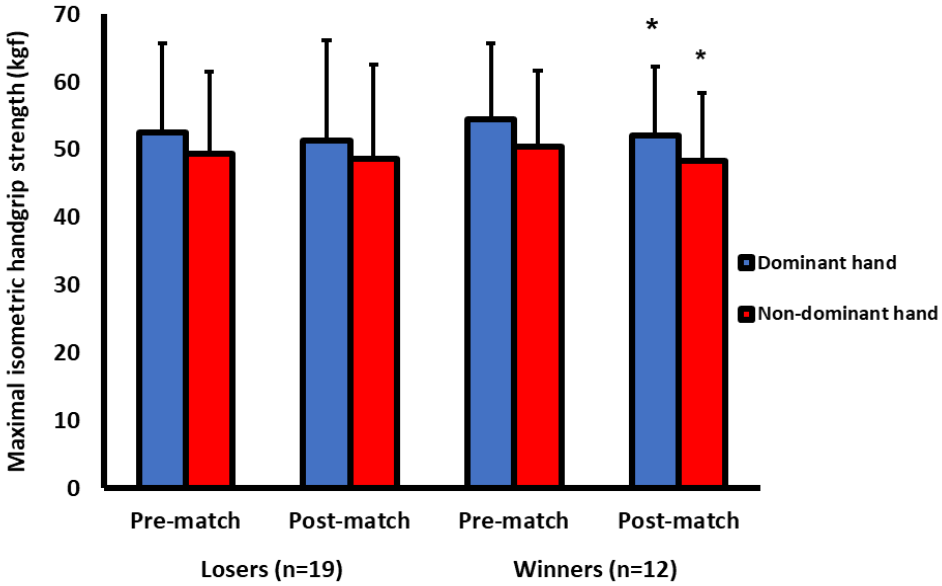


Figure 23: Maximal isometric handgrip strength after and before an official kickboxing match (adapted from Tassiopoulos and Nikolaidis [54]).

Note: the data represent the mean and standard deviation; * = different of pre-match values of dominant hand (p<0.001); ** = different of pre-match values of non-dominant hand (p<0.05).

The results indicated decreases in the maximal isometric handgrip strength after official kickboxing matches for both the dominant and non-dominant hands in these athletes. Figure 24 presents the maximal isometric handgrip strength values before and after the combats of winning and losing athletes.



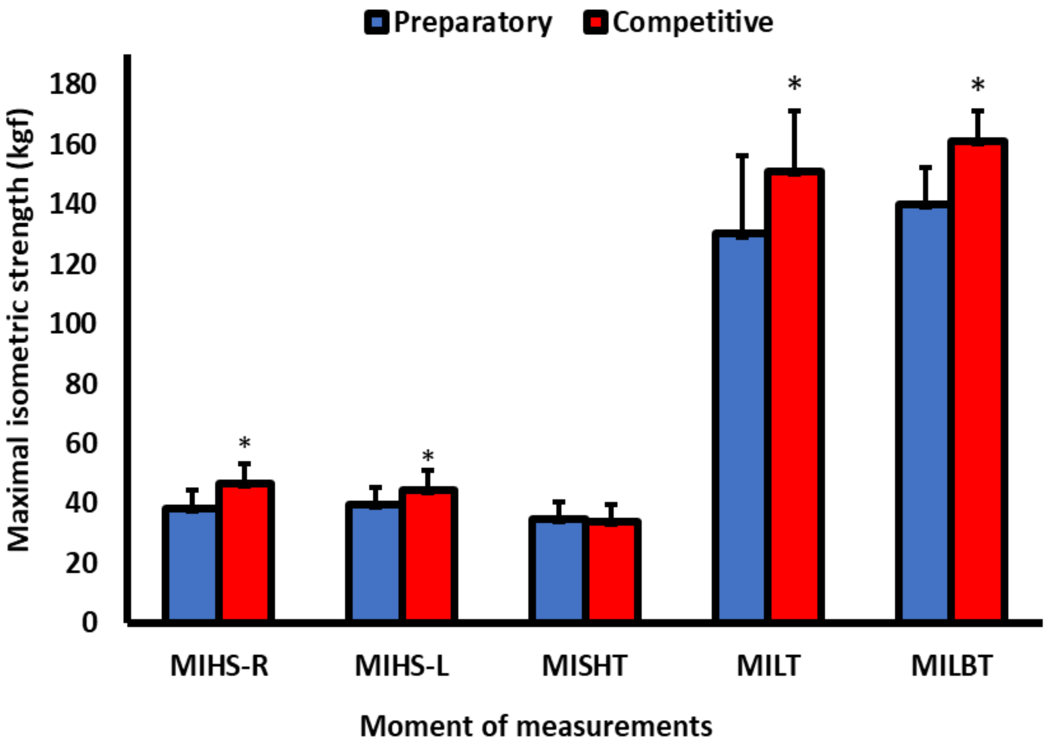
Note: the data represent the mean and standard deviation; * = different (p<0.001) of pre-match values of the winners' athletes.

Figure 24: Maximal isometric handgrip strength of the winners and loser's kickboxing athletes (adapted from Tassiopoulos and Nikolaidis [54]).

The results presented in figure 24 indicate decreases in the maximal isometric handgrip strength of the winning athletes. However, no differences were identified among the defeated athletes. Moreover, the authors reported that the decrease in the maximal isometric handgrip strength could be associated with high neuromuscular fatigue. This factor was not supported by the results identified in the loser athletes. Moreover, the maximal isometric handgrip strength was shown to differentiate the athletes according to the performance obtained in the matches (victory or defeat). However, because it is striking combat sport, that is, a sport that involves the execution of kicks, punches, elbows, and knees, the measurements of the maximal dynamic and isometric strength in other exercises, such as bench press, squat, chin-up, and stiff, appear to be more specific than the use of handgrip strength, which is usually performed in the grappling combat sports. This occurs because the muscular demand in the handgrip's execution is substantially greater in the grappling modalities than in the striking modalities. However, for the MMA, using the dynamometer to measure the maximal isometric handgrip strength is valid since the forearm musculature is needed to perform throwing techniques, immobilizations, and finalizations during the matches. The authors also consider that coaches and physical trainers may use this study's results during training and competitions. However, the study has caveats (regarding the dynamometer's use as an instrument for evaluating kickboxing athletes). Based on these aspects, new research should be carried out, considering that the study mentioned above was the first to assess the differences in the maximal isometric handgrip strength between winners and losers during an official kickboxing competition.

4. Longitudinal studies on the development of maximal strength in combat sports athletes

To verify the influence of the training period on the maximal isometric strength in different tests, body composition, and somatotype (these two last ones are not part of this chapter), Franchini et al. [55] submitted 8 juvenile judo athletes (15-16 years old) to a series of maximal isometric strength tests: 1) right and left handgrip; 2) lumbar traction; 3) lower-body traction and 4) scapula-humeral traction. The measurements were performed one month after the start of the preparation period. In contrast, after the fourth month, the follow-up occurred 20 days after the beginning of the competitive period. The athletes performed the same training model during the four months, which consisted of the judo-specific training 3 to 4 times a week with a duration of approximately 2 hours per training session and physical preparation in the weight room 2 to 3 times a week, which aimed to improve muscle power (3 to 4 sets of 6-8 repetitions were performed at 80% of 1RM for the main muscle groups). Additionally, in this study, no athlete reported to be using rapid weight loss procedures. Figure 25 shows the values of the maximal isometric handgrip strength, lumbar traction, lower-body traction, and scapula-humeral traction of the athletes in the preparatory period and 20 days after the start of the competitive period.



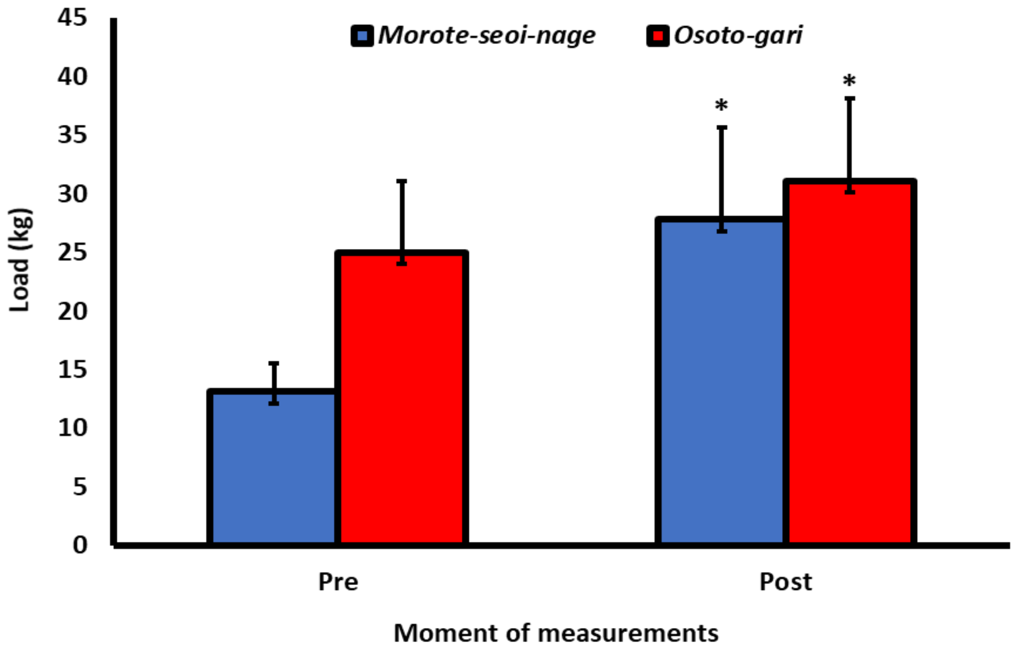
Note: the data represent the mean and standard deviation; * = different of measured values in the preparatory period when compared to competitive period of the judo athletes (p<0.01); MIHS-R = maximal isometric handgrip strength of right hand; MIHS-L = maximal isometric handgrip strength of left hand; MISHT = maximal isometric scapulo-humeral traction; MILT = maximal isometric lumbar traction; MILBT = maximal isometric lower-body traction.

Figure 25: Maximal isometric strength in different dynamometers (adapted from Franchini et al. [55]).

According to figure 25, there were increases in the measurements obtained during the competitive period for the right and left handgrip strength, lumbar traction, and lower limb traction compared to the athletes' measures in the preparatory period. However, no differences were found for scapula-humeral traction at the two measurement moments. It is plausible to note that this study did not present a control group since the sample was composed of adolescents. Consequently, it is difficult to consider the increase only because of the training's adaptations. The tests performed to measure the athletes' gains were not specific to the training program since they performed dynamic exercises. In contrast, the measurements of maximal strength were performed using isometric tests.

The study by Blais and Trilles [56] analyzed the performance of judo athletes submitted to a specific device strength training program, in which 20 experienced French judokas (black-belts) were randomly assigned to two groups: control (age 23 ± 2.4 years old, n = 10) and experimental (age 22 ± 3.6 years, n = 10). The strength training program lasted 10 weeks. The control group did not perform other training, for example, strength training in the judo-specific equipment. The experimental group completed strength training twice per week with 5 sets of 10 repetitions in the judo-specific equipment, combined with the same number of throwing technique executions (*nage-komi*) with the training partner. The specific exercises simulated the technique *morote-seoi-nage* and *o-soto-gari*, and the throwing techniques were performed from these exercises. A video recording was performed before and after the groups' training period to evaluate the quality of the throwing techniques. To this end, 23 expert coaches from the French judo team evaluated each athlete's performance, assigning scores from 0 to 20. Figure 26 shows the maximal dynamic loads for the *o-*

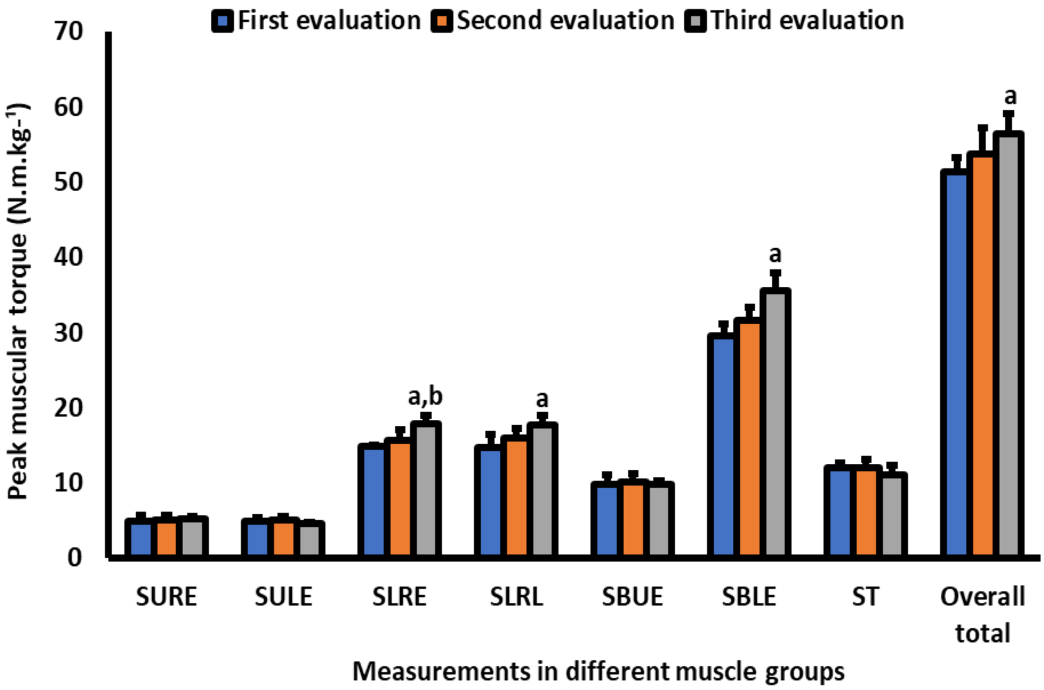
soto-gari and *morote-seoi-nage* techniques in the specific equipment before and after 10 weeks of training. The results showed improvements for the *o-soto-gari* and *morote-seoi-nage* techniques compared to the training period's measurements. Besides, the group that performed strength training in the judo-specific equipment and throwing techniques showed an improvement in the quality of the two techniques in the grades attributed by the experts (*o-soto-gari:* 6.4 ± 2.5 for 9.4 ± 2.4; *morote-seoi-nage:* 8.2 ± 2.7 for 9.6 ± 2.6), whereas the control group did not show an improvement in the grades attributed to the throwing techniques. Thus, the progress after the experimental group athletes' training period was quantitative, with the increase of the loads in the exercises and qualitative, through the experts' grades.



Note: the data represent the mean and standard deviation; * = different of measured values before the training period (p<0.05).

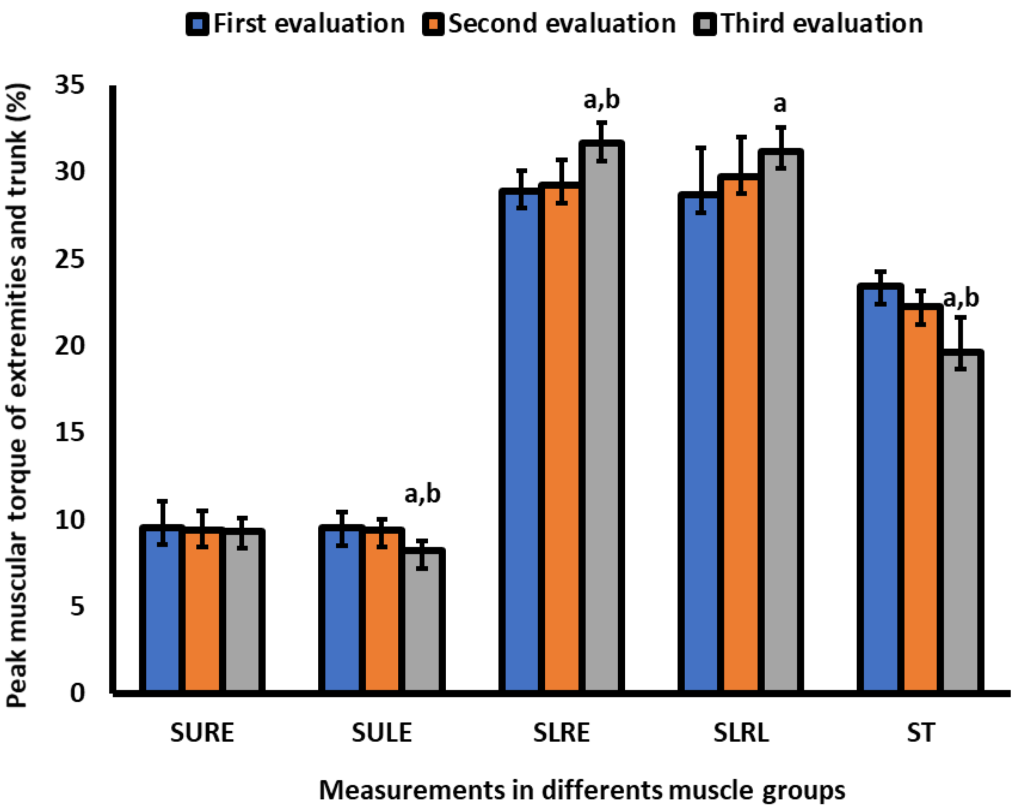
Figure 26: Maximal dynamic strength for the techniques: *o-soto-gari* and *morote-seoi-nage* in specific apparatus after and before training period (adapted from Blais and Trilles [56]).

The research developed by Buśko and Nowak [57] aimed to examine the peak torque differences in judo athletes during the pre-competitive period. The study participants included 5 athletes from the Polish judo team who performed a battery of tests on isokinetic equipment. The measurements were performed in three moments: 1) before the pre-competitive period, 2) immediately after the strength training mesocycle, and 3) immediately after the pre-competitive period. Peak torque was measured in 10 muscle groups: flexors and extensors of elbow and knees, shoulders, hip, and trunk. All measurements occurred in static conditions. For the shoulders, the 70º angle for flexion and the 50º angle for extension were used, for the knees and hip, the test occurred at 90º, and for the elbows, knees, and hip, the angles tested were at 0º. The athletes were instructed to perform the tests in the highest possible power, and all measurements were performed in the morning. Figure 27 shows the sum of the maximal peak torque values for the elbows, knees, shoulders, hip, and trunk of the evaluated athletes. The findings indicated an increase in the sum of the right lower extremity in the 3rd assessment (immediately after the pre-competitive period) compared to the 1st (before the pre-competitive period) and 2nd (immediately after the strength training) measurements. Similarly, the present results showed a marked increase in the 3rd evaluation for the lower-left extremity summation than the 1st evaluation performed. Specifically, regarding the sum of both lower limbs, the findings showed marked increases in the 3rd evaluation compared to the 1st evaluation. Finally, there were accentuated elevations for the total and the total sum in the 3rd evaluation compared to the 1st evaluation. Figure 28 shows the sum of the peak torque values for the right and left upper extremities, right and left lower extremities, and summation of the trunk with values expressed in (%), before the pre-competitive period, immediately after the strength training mesocycle, and immediately after the pre-competitive period.



Note: the data represent the mean and standard deviation; a = different of first evaluation ($p < 0.05$); b = different of second evaluation ($p < 0.05$); SURE = sums of the upper right extremities; SULE = sums of the upper left extremities; SLRE = sums of the lower right extremities; SLRL = sums of lower left extremities; SBUE = sums of both upper extremities; SBLE = sums of the both lower extremities; ST = sums of the trunk.

Figure 27: Peak torque of different body regions after the mesocycle strength training and after the mesocycle pre-competitive period (adapted from Buśko and Nowak [57]).

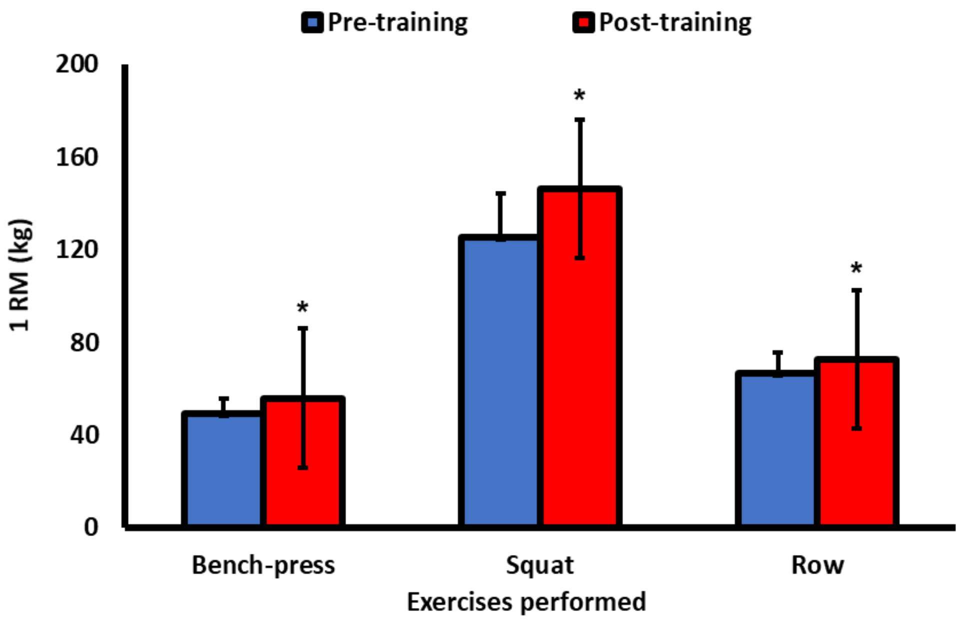


Note: the data represent the mean and standard deviation; a = different of first evaluation ($p<0.05$); b = different of second evaluation ($p<0.05$); SURE = sums of the upper right extremities; SULE = sums of the upper left extremities; SLRE = sums of the lower right extremities; SLRL = sums of lower left extremities; ST = sums of the trunk.

Figure 28: Peak torque of different body regions in percentages after the mesocycle strength training and after the mesocycle pre-competitive period (adapted from Buśko and Nowak [57]).

The results indicated an absence of differences in all measurements obtained for the sum of the upper right extremity. However, significant decreases were found for the sum of the left upper extremity in the 3rd evaluation (immediately after the pre-competitive period) compared to the 1st and 2nd measurements. For the lower right extremity, marked elevations were found in the 3rd evaluation compared to the 1st and 2nd evaluations. Similarly, the findings showed marked increases for the 3rd evaluation compared to the 1st measurement. A sharp decrease was found in the 3rd evaluation compared to the 1st and 2nd evaluations about the trunk sum. We can verify that this study has some limitations as follows: 1) The relatively low number of participants (n = 5); 2) The number of exercises, sets, muscle groups, and repetitions during the strength training mesocycle were not reported; and 3) The evaluations were conducted in an isokinetic equipment, in which the measures were performed unilaterally; thus, it does not reflect the demand of the real match, as the judo match uses multi-articular actions that solicited in different ways.

Still, the study conducted by Stojanovic et al. [58] aimed to increase the performance of judo athletes through an 8-week training program with strength, aerobic and anaerobic exercises (these last two aspects are not part of this chapter) during the pre-competitive period. To this end, 11 junior and senior female athletes who belonged to the Serbian judo team were recruited with high international experience. The training was divided into two 4-week mesocycles, as a 3:1 periodization model; that is, 3 weeks of training were performed with a gradual increase of the load, followed by a week of reduction (recovery). For the first mesocycle, 60% of the exercises performed were non-specific, and 40% were judo-specific exercises; that is, strength training was conducted 3 times a week for four weeks. The exercises performed were as follows: bench press, squat, and row. Two sets were performed for each exercise between 7-10 repetitions with loads between 70 and 80% of 1RM. There was inversion between judo-specific and non-specific exercises for the second mesocycle, with 60% of judo-specific exercises and 40% for non-specific exercises; strength training was performed twice per week four weeks. The non-specific exercises performed were as follows: strength training (in the weight room), high-intensity interval exercise, and high-intensity anaerobic exercise (these two last aspects are not part of this chapter), whereas the specific exercises had a technical-tactical nature. Figure 29 shows the values of 1RM for bench press, row, and squat before and after 8 weeks of training.

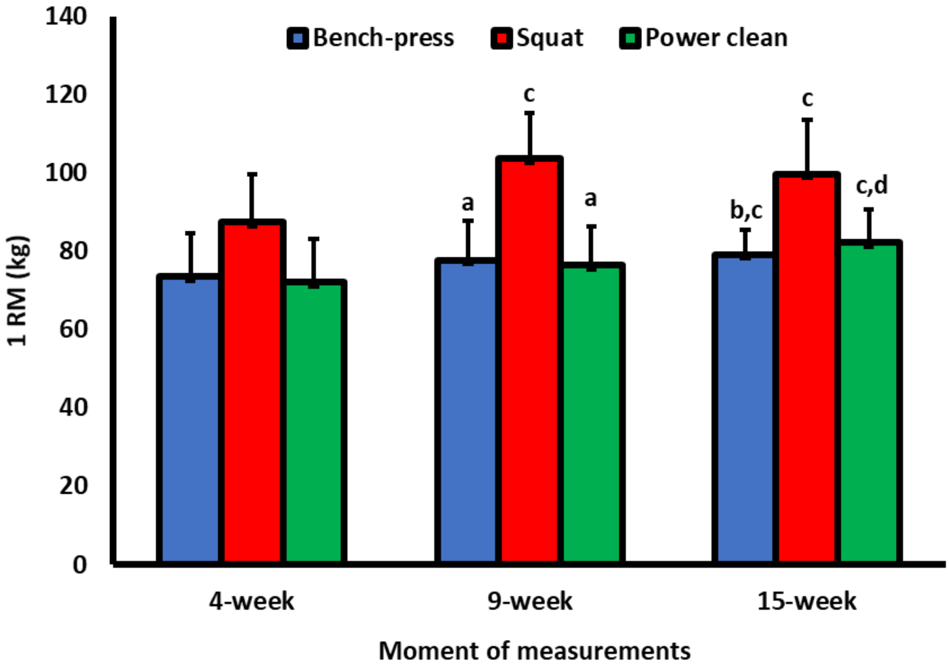


Note: the data represent the mean and standard deviation; * = different pre-training values (p<0.05).

Figure 29: One repetition-maximum (1 RM) values for the bench-press, squat and row after and before 8-week strength training (adapted from Stojanovic et al. [58]).

The results showed marked elevations after 8 weeks of training for the bench press (13.7%), squat (16.5%), and row (8.8%) compared to the measurements obtained before the training period. Also, it is noteworthy that the low volume of the exercises performed during the 8 weeks of training promoted large increases in the trained judoka's maximal strength in the pre-competitive period. Thus, the exercises used in this study can serve as a reference for the prescription of training by professionals responsible for the physical preparation of athletes to maximize the competitive performance.

Passelergue and Lac [59] recruited 15 French Olympic wrestlers (aged: 17.9 ± 0.2 years) with international experience. Most of the athletes were trained in Greco-Roman and freestyle (n = 10), while others (n = 5) trained only in the Greco-Roman style. The athletes trained, on average, 12 to 15 hours per week. The training periodization was carried out between September and December, which was carried out before the competitive period. The training was divided into 3 periods: 1) P1- Consisted of maximal strength exercises for 7 weeks (and other exercises that are not part of this chapter; 2) P2- Athletes had a week of rest because of school vacations; and 3) P3- Maximal strength and power exercises were executed for 6 weeks (among other exercises not related to the purposes of this chapter). The first training session consisted of 5 sets of 8-12 repetitions between 70 and 80% of 1 RM. The second session was performed using 5 sets of 2-5 repetitions with 85 to 95% of 1RM, with an approximate duration of 45 min per training session. The third session comprised the execution of sets for maximal strength maintenance, composed of 1-3 sets of 2-5 repetitions with loads between 85 and 95% of 1RM. Exercises, such as bench press, military press, front pull, squat, leg-press, deadlift, biceps, triceps, and trunk exercises, were performed during the training period with approximately 2 to 3 min of rest between sets. Also, weightlifting exercises, such as clean, snatch, deadlifting, and weight-bearing exercises that mimicked Olympic wrestling's specific actions, were prescribed. Figure 30 presents the maximal strength values for the bench press and squat.



Note: the data represent the mean and standard deviation; a = different of the measures performed in the 4th training week ($p < 0.05$); b = different of the measurements performed in the 9th training week ($p < 0.01$); c = different of the measurements performed in the 4th training week ($p < 0.01$); d = different from the 9th training week ($p < 0.05$).

Figure 30: One repetition-maximum (1 RM) for the bench-press, squat, and power clean for the French junior judo athletes of wrestling submitted to 15th of strength training (adapted from Passelergue and Lac [59]).

Concerning figure 30, the presented results indicated elevations in the bench press's maximal strength at the 9th week compared to the measurements obtained in the 4th week. Similarly, marked elevations were identified in the evaluations conducted in the 15th week compared to the 4th and 9th weeks, respectively. The findings indicated marked gains for 1RM in the evaluations performed in the 9th and 15th weeks compared to the squat's 4th week. Regarding the power clean, the results showed increases in the maximal strength for week 9 compared to the measurements obtained in week 4. Similarly, the results showed high gains in the evaluations conducted at the 15th week compared to the 4th and 9th weeks of training.

One limitation of this study is the lack of evaluations in the first week of training since the results could indicate the athletes' initial level of physical conditioning and tests of 1RM in the other exercises used in the training program. Although this study was conducted concomitantly with aerobic training, as it could characterize it as a concurrent training and potentially minimize the benefits resulting from strength training, the findings indicated marked increases in 1RM tests in all exercises measured. However, the proposed periodization may be a relevant alternative for professionals working in Olympic wrestlers' training because strength, power, strength-endurance, and aerobic and anaerobic fitness are significant for maximizing and maintaining performance in the matches. It is also worth mentioning that the adoption of complementary training methods must be continuously monitored. In many instances, recovery between training sessions is neglected. Therefore, the insertion of questionnaires for monitoring training and the use of heart rate variability (HRV) [60] to assess autonomic activity and performance tests, such as the countermovement jump, may be used to monitor athletes.

In turn, the research conducted by Fukuda et al. [61] had as objective to verify the physiological adaptations during four weeks of training in children and adolescents during the competitive period in judo. The adolescent athletes were in the intensive preparation phase for the Junior American National Championship, and all participants underwent a test battery before and after the training period. Judo practitioners (male, n = 10, female, n = 10) participated in the study as follows: 1) children 7 to 12 years old (n = 8) and 2) adolescents: 13-19 years old (n = 12). Besides, the judo athletes performed the maximal isometric handgrip strength (among other tests that are not part of this chapter). The physical, technical, and tactical preparation consisted of eight training sessions, which lasted approximately 16 hours of training a week. The morning and evening training sessions were conducted four times a week (morning workouts: Tuesday, Wednesday, Thursday, Saturday, and Monday; evening workouts, Tuesday, Wednesday, and Thursday). The morning training routine involved the execution of stretching exercises (~10 min), interval running (~20 min), weight-bearing exercises, plyometrics, bearings and *ukemi* (~20 min), throwing techniques (~10-15 min), groundwork combat or *ne-waza uchi-komi* (~ 20 min) and *randori* (~20 min). Also, at the end of each training, the participants were instructed to climb a 9 m rope (2 x per training). The afternoon training routine comprised the execution of rapid and dynamic warm-up exercises (~15 min), specific throwing techniques exercise (~15-20 min), static *nage-komi* or static *uchi-komi* (15-20 min), groundwork combat or *ne-waza uchi-komi* (~20 min), static and moving throwing techniques (~20 min) and the execution of interval sprint exercises in circuit (~10-15 min). Figure 31 shows the maximal isometric strength values for children and adolescents before and after 4 weeks of training.

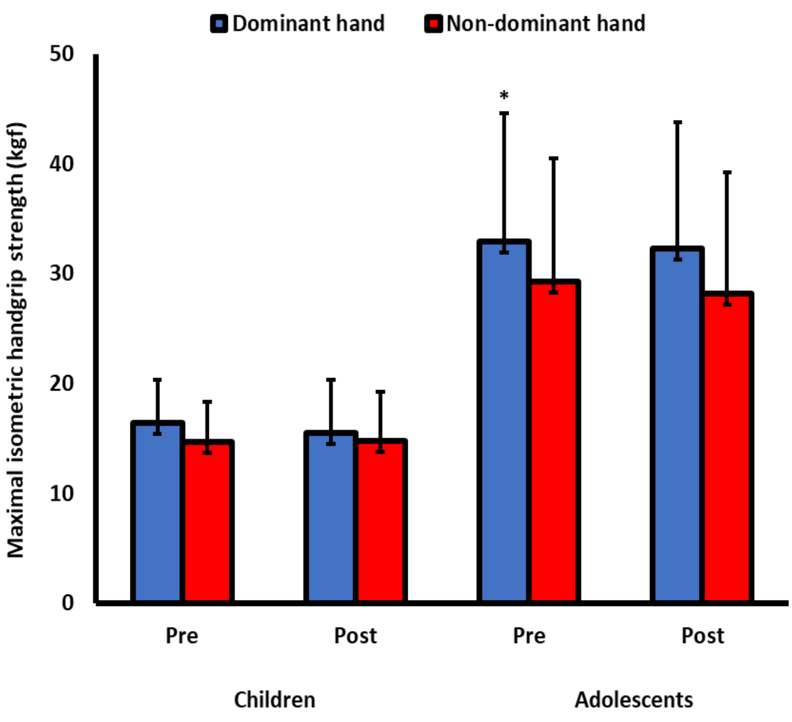
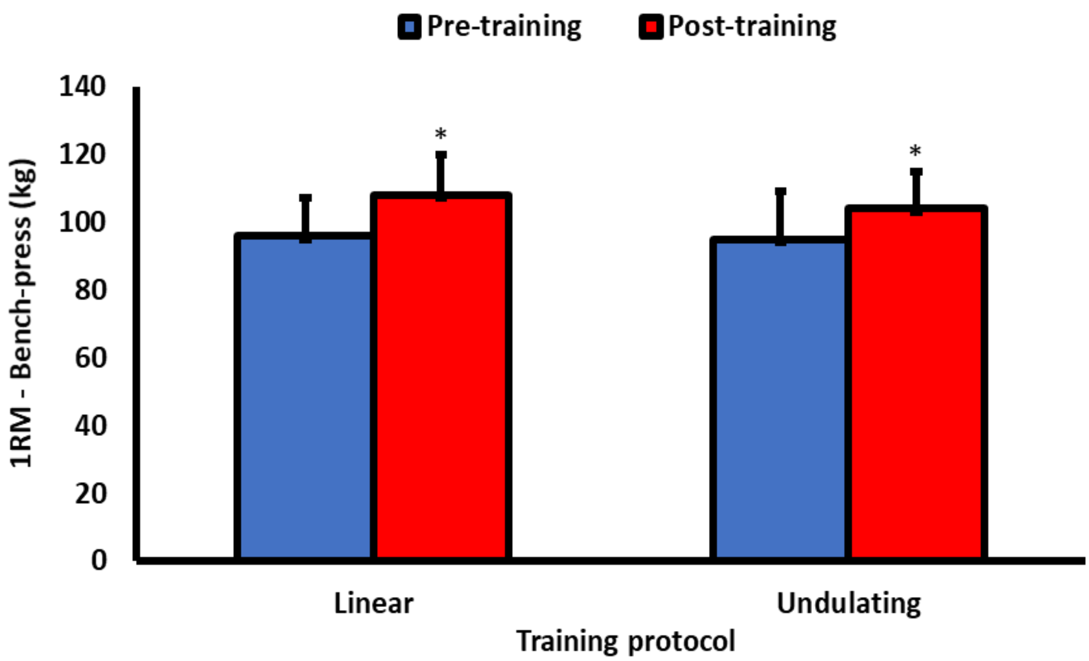


Figure 31: Maximal isometric strength in children and adolescents after and before 4-week strength training (adapted from Fukuda et al. [61]).

Note: the data represent the mean and standard deviation; * = different of the pre-training measures between children and adolescents ($p<0.05$); pre = pre-training; post = post-training.

The results showed differences in the maximal isometric handgrip strength in the evaluations performed before the training period, with higher values for adolescents than those for children. However, no differences were found for the maximal isometric handgrip strength between measurements before and after the groups' training period (children and adolescents). Consequently, the results are not surprising since the judo-specific training involves grip disputes, and the rope climbing is predominantly related to strength-endurance. As a result, we can understand the absence of differences between the evaluations performed before and after the training period for the maximal isometric handgrip strength. In this respect, the maximal dynamic and isometric *judogi* chin-up seem to be more specific for assessing the handgrip strength-endurance than the test using the dynamometer since the flexor's strength-endurance and extensor muscles of the forearm are very important for maintaining the grip during the match [62]. A substantial limitation of the study is the control group's absence, as athletes were developing. The authors also noted that the children's gains could not be measurable through the tests used. Finally, the study carried out by Fukuda et al. [61] was the first to analyze body composition and specific measures of performance in judo athletes in these age groups (7 to 12 and 13 to 19 years old) and can be used as a reference for professionals involved in children's and adolescents' training in this sport.

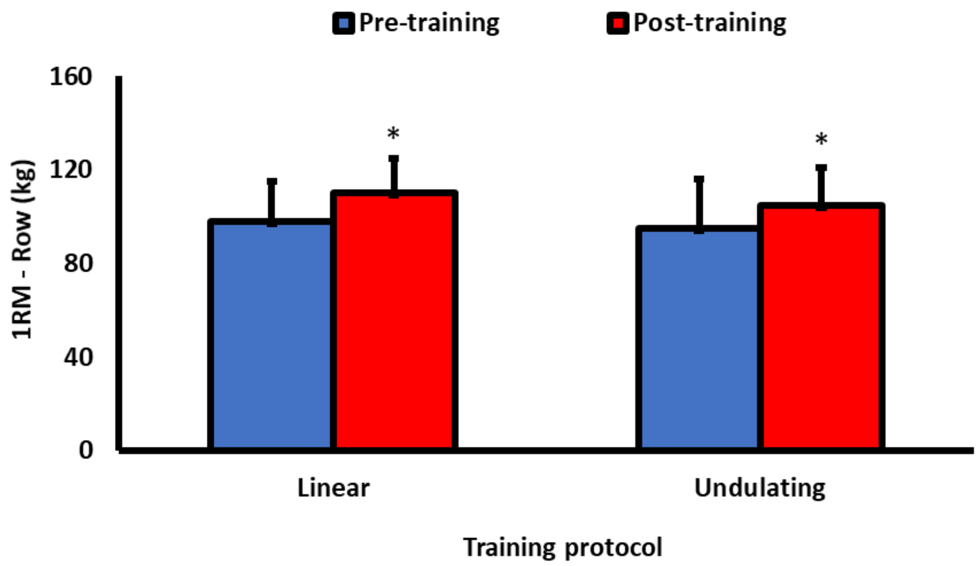
The research developed by Franchini et al. [63] had the purpose of investigating the effects of linear and undulating periodization during 8 weeks of training in judo athletes. Thirteen athletes were randomly divided into linear (n = 6) and undulating (n = 7) groups. The athletes were submitted to maximal strength tests of 1RM for bench press, row, and squat, among other measures not included in this chapter. Four sets were performed for all exercises, and the two groups trained 3 times a week with the following exercises: 1) bench press, 2) squat, 3) bar lying row, 4) arm-curl, 5) lying triceps extension, 6) leg curl, 7) barbell writs curl, 8) dumbbell frontal raise, 9) dumbbell lateral raise, 10) good-morning, 11) reverse wrist curl and 12) Smit standing leg calf raise. The training division was performed as follows: 1st training day: exercises from 1 to 8; 2nd training day: exercises 5 to 12; and t 3rd training day: exercises 1 to 4 and 9 to 12 for both groups. The periodization for the linear group was conducted as follows: the 1st and 2nd weeks of training included exercises from 3 to 5 RM, the 3rd, 4th, and 5th weeks included power exercises (between 6 and 8 repetitions), and in the 6th, 7th and 8th weeks, the 15-20 RM exercises were performed. For the undulating training group, stimuli of 3 to 5 RM, power, and 15-20 RM were alternated. Figure 32 presents the values of 1RM for the bench press of the athletes who performed the linear and undulating periodization.



Note: the data represent the mean and standard deviation; * = different (p <0.05) of pre- and post-training period.

Figure 32: One repetition-maximum (1 RM) for the bench-press after and before 8-week linear and undulating strength periodization in judo athletes (adapted from Franchini et al. [63]).

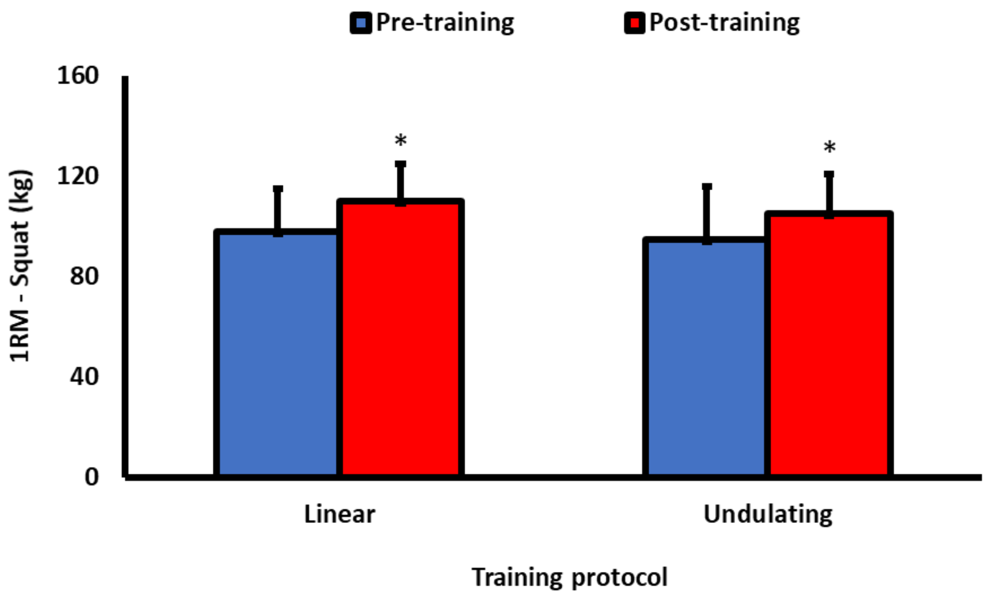
The results presented indicated marked increases in the maximal strength test for the bench press after the athletes' training period submitted to the linear and undulating protocols compared to the measurements performed before the training period for both groups. The increase in the maximal strength on the bench press for both groups was 11.6% after the training period concerning the measurements performed before this period. Figure 33 shows the values of 1RM for the squat exercise for the athletes who completed the linear and undulating periodization.



Note: the data represent the mean and standard deviation; * = different ($p<0.05$) of pre- and post-training period.

Figure 33: One repetition-maximum (1 RM) for the row after and before 8-week of linear and undulating strength periodization in judo athletes (adapted from Franchini et al. [63]).

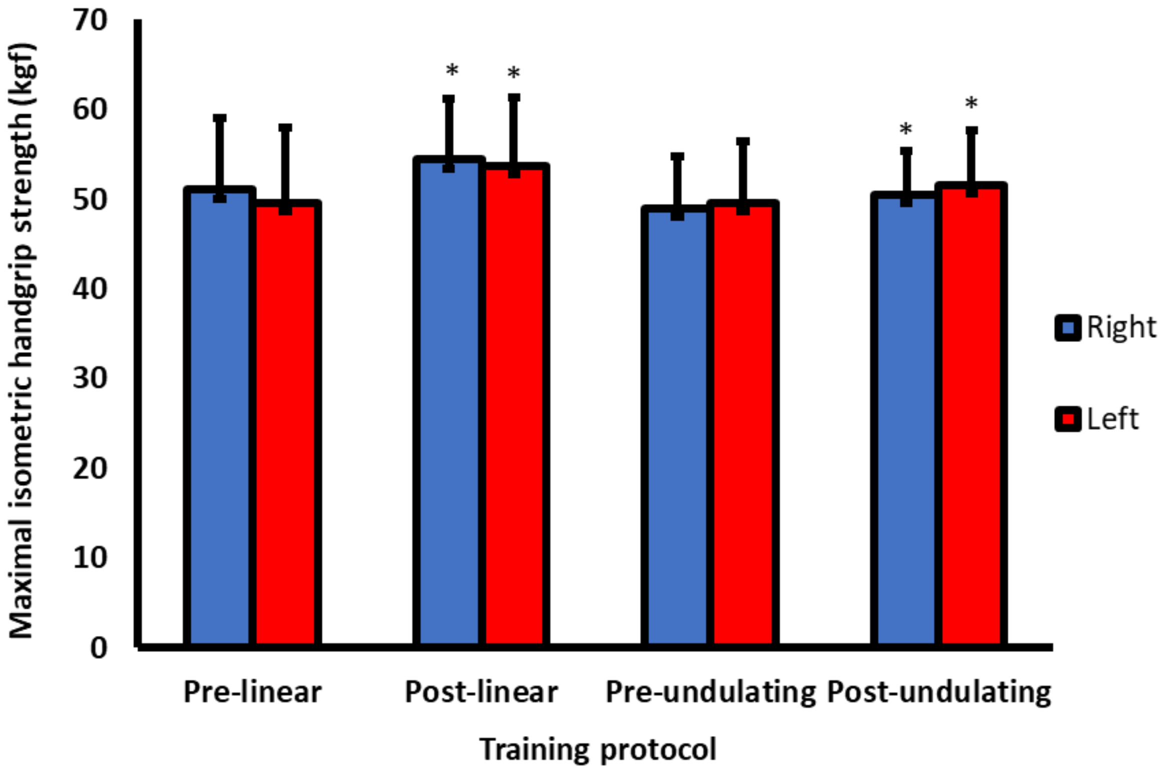
Regarding figure 33, the presented results indicated marked increases in the maximal strength test for squat after the athletes' training period submitted to the linear and undulating protocols compared to the measurements performed before the training period for both groups. Additionally, the increase in the maximal squat strength for both groups was 7.1% after the training period about the training period's measurements. Figure 34 presents the values of 1RM for the bar lying row of the athletes who performed the linear and undulating periodization.



Note: the data represent the mean and standard deviation; * = different ($p<0.05$) of pre- and post-training period.

Figure 34: One repetition-maximum (1 RM) for the squat after and before 8-week linear and undulating strength periodization in judo athletes (adapted from Franchini et al. [63]).

The results presented indicated increases in the maximal strength test for the bar lying row after the athletes' training period submitted to the linear and undulating protocols compared to the measurements performed before the training period for both groups. The increase in the maximal resting strength for both groups was 11.5% after 8 weeks of training to the measurements performed before this period.



Note: the data represent the mean and standard deviation; * = different ($p<0.05$) of pre and post-training period.

Figure 35: Maximal isometric handgrip strength for right and left hands after and before 8-week of linear and undulating strength periodization in judo athletes (adapted from Franchini et al. [63]).

Regarding figure 35, the findings show an increase in the maximal isometric handgrip strength for the right and left hands after the training period compared to the measurements performed before the training period for both training models (linear and wave). The maximal isometric strength increases were 4.6% for the right hand and 6.1% for the left hand. From the data presented, no differences were detected between the two training models, and it should be emphasized that further longitudinal studies of longer duration should be performed. The authors also suggest that incorporating other training methods, such as weightlifting exercises, complex training connecting strength exercises to specific actions of judo, could be investigated. These methods can be tested to determine the most efficient model to maximize athletes' performance during training and competitions.

Studies analyzing periodized judo training for longer than three months are not frequently conducted [64,65]. Franchini et al. [64] submitted state-level judo athletes to a general phase, for 7 weeks, involving strength training directed to muscle hypertrophy for the main muscle groups (8 to 12 exercises, 3 sessions a week, 4 x 8-12 repetitions at 70-80% of 1RM), together with other exercises (*randori*: 4 times a week at 60% of maximal perceived effort, 6-8 5-min matches with 5 to 10 min intervals; aerobic conditioning: running, 2 sessions a week, for 40 to 60 min, at 60% of heart rate reserve). After this general phase, athletes executed the following training for 11 weeks: (A) Strength training - the first 8 weeks with basic strength training exercises and the last 3 weeks with complex training (3 sessions a week). Basic strength was developed by using wrist flexion exercises, triceps and back pulley machines exercises, rowing, squat, Olympic-type lifts (e.g., power clean, high pull, clean and jerk, snatch), performed at high-intensity (4 x 3–5 repetitions at ~90% of 1RM, and the highest speed possible, with 3 min intervals between sets). Complex training was composed of

Olympic-type lifts, squat and bench press exercises, at the same intensity and volume used in the previous 8 weeks, but followed by specific judo actions (mainly throwing judo techniques, 3–5 repetitions with different partners, 3–5 min after the maximal strength exercise); (B) *Randori* - intensity during this phase was increased to 70–90% of maximal effort (7–9 in the 0–10 Borg scale), using 4 to 6 combats with longer intervals (5–10 min) between matches, using the same number of sessions per week; (C) Aerobic training - the intensity for the aerobic training also increased (90–100% of heart rate reserve, twice a week), performed intermittently (1:1 effort: pause ratio) and in a lower volume (30 min per session). Concerning maximal strength adaptation, after the 18 weeks of training, only row exercise 1RM significantly increased from pre- (85 ± 23 kg) to post- (92 ± 26 kg), whereas right (pre: 61 ± 13 kgf; post: 60 ± 13 kgf) and left (pre: 54 ± 12 kgf; post: 55 ± 10 kgf) maximal isometric handgrip strength, and bench press 1RM (pre: 88 ± 24 kg; post: 91 ± 23 kgf) did not change significantly. The authors attributed the only change in the row exercise to the frequent execution of pulling actions during judo matches. Despite the constant grip dispute, the changes were observed in strength-endurance variables and not in maximal isometric handgrip strength (see chapter about strength-endurance). Therefore, the adaptation to this type of training was related to the specificity of actions and the match physical demand.

Marques et al. [65] applied block periodization concepts to national and international level judo athletes and compared their responses to such training process, with five weeks of accumulation phase, five weeks of transmutation phase, and three weeks of realization phase. During the accumulation phase, athletes executed strength exercises and conditioning workouts to develop judo-specific strength (i.e., muscle power in lower- and upper-body and strength-endurance in upper-body - especially the forearm muscles - and core regions). For the transmutation phase, training was directed to develop muscle power, including weight training, plyometrics, and judo-specific actions. During the realization phase, the training was like the transmutation phase, but the volume was reduced, and judo technical actions were the main focus of the training phase. Among muscle power, judo-specific test performance, row 1RM test was the only maximal strength-related variable assessed. For this variable, lower relative values were observed after the accumulation phase (national level: 0.76 ± 0.22 kg/kg of body mass; international level: 0.77 ± 0.15 kg/kg of body mass) compared to before the accumulation phase (national level: 1.05 ± 0.24 kg/kg of body mass; international level: 1.09 ± 0.17 kg/kg of body mass) and after the transmutation phase (national level: 1.08 ± 0.26 kg/kg of body mass; international level: 1.13 ± 0.17 kg/kg of body mass).

However, no effect of competitive level was detected. This result indicated that the row exercise maximal strength test was sensitive to detecting the training content changes imposed during the block periodization. Therefore, the findings provided evidence to support the suggestion for isolating voluminous physical training content (i.e., similar to that used in the accumulation phase in the study) and intensive sport-specific training into appropriate block mesocycles, and that the row exercise can be used to monitor changes in the maximal strength of judo athletes submitted to such periodization.

Øvretveit and Tøien [66] assessed the short-term effects of strength training on 14 male Brazilian jiu-jitsu (BJJ) athletes' generic performance. In this chapter, we focused only on strength response; the athletes performed a 1 RM test for bench-press and squat (in addition to other exercises that are not part of this chapter). The athletes were randomized into two groups: an experimental and a control group. For four weeks, the athletes carried out 4 x 4 repetitions at > 85% of 1 RM in the squat and bench-press, and pull-ups until failure, three times a week. The athletes presented different BJJ experience levels (white belt, blue belt, or purple belt). During the training planning, both groups performed the same BJJ training routine. After four weeks, an improvement of 15 ± 9% was identified for the bench-press 1RM and 11 ± 3% for the squat 1RM. The authors concluded that strength training's low-volume training could improve BJJ athletes' maximal strength.

4.1 Final considerations on longitudinal studies in combat sports

Finally, it is pertinent to consider that scientific studies remain scarce for combat sports. Thus, it is deemed essential to develop longitudinal studies that contemplate each modality's peculiar characteristics to aid coaches and physical trainers in the prescription of the training and, consequently, improve the competitive performance.

5. Maximal strength tests for combat sports athletes

5.1 Maximal dynamic strength tests

Maximal dynamic strength tests are performed to measure the maximum load an athlete can perform in each exercise, which is described as a 1 RM [10]. Exercises such as bench press, squat, and row may be used to assess the maximal strength [27] and the snatch and the clean and jerk Olympic weightlifting exercises, commonly used in the physical preparation of combat sports athletes [7,67]. The maximal strength exercises can be performed in the weight room using bars, dumbbells, and other accessories, with specific modality gestures/movements [11]. To complete the 1RM test, it is recommended that the athlete follows the American Society of Exercise Physiologists (ASEP) procedures described by Brown and Weir [68]. A specific warm-up should be performed for the exercises, which will be tested using a 5-rep set with a load of 50% of the estimated 1RM and a 3-rep set with 70% of the estimated value for the 1RM, with a 2 min interval between the sets. The testing of 1RM should be performed at least three times and at most five times, with rest intervals of 3 to 5 min.

5.2 Isokinetic test

To perform the maximum torque evaluations, specialized equipment considered as the gold standard is used to analyze the balance of different muscle groups. Measurements can be completed in physical conditioning programs and physical therapy rehabilitation, which provide highly accurate and reliable data [19]. It is worth mentioning that the isokinetic test has been widely used to measure muscle imbalances between the right and left sides, as well as between the antagonistic muscle groups in certain actions and, are usually indicated after injuries or surgeries that keep athletes away from training and competitions [43–45,69].

5.3 Maximal isometric strength tests

The maximum isometric strength tests can be performed on the following devices: 1) In bar, when coupled to a load cell connected to a computer, the results are sent to a specific software as executed in the study of Fernandez et al. [37]; 2) In one particular dynamometer for handgrip, lumbar, lower-body or scapula-humeral traction, as described by Franchini et al. [55]. During isometric exercise, there are no stretching and shortening muscles' actions. Moreover, the tension exerted may be higher than eccentric and concentric muscle activity [1,70]. In the topic intended for the prescription, the angles maximal isometric strength development will be indicated in some exercises.

5.4 Safety, injury prevention, and soreness during strength training

Injuries during strength training have been associated with failure to establish safety guidelines. Athletes and/or coaches who avoid performing strength training in the physical preparation routine were probably misguided in the physical sports training process [71]. The same authors also point out that qualified instruction and adherence to the proper technique promote a low risk of injury. In the same direction, the systematic review with meta-analysis published by Lauersen et al. [72] indicates the existence of a dose-response relationship between strength training and injury prevention. It is worth mentioning that supplementary strength training and the physical, technical, and tactical training of athletes should be monitored. Indirect measures, such as the rating of perceived exertion, rating of perceived recovery, sympathetic and parasympathetic responses, via heart rate variability, and performance tests, such as the countermovement jump, could be conducted [60]. Direct measures can also be undertaken, such as blood collections to determine biomarkers, anabolic and catabolic hormones. However, these measures have a higher cost, sometimes making direct analyzes limited to professional clubs or research centers [60]. Thus, the monitoring of physical-sports training can provide the technical commission and staff with tools to control the training load and reduce the risk of possible injuries.

The literature also points out that strength training is essential for athletes' rehabilitation in pre- and post-surgical sports injuries [73,74]. A general warming up can be performed via aerobic exercises, such as jogging, cycling on a cycle ergometer and even, performing exercises that mimic specific gestures used in the respective combat sport to increase athletes' arousal, attention, and likely performance during the subsequent tasks [11]. According to Harmon et al. [71], exercises such as: walking knee hugs, cross-knee hugs, skip series, walking lunges, walking hamstrings and quadriceps stretches, inch worms, high knees, and butt kickers may be conducted to promote general warming up. The same authors recommended that this warm-up method be performed in series of 10 to 20 meters. These authors also emphasized that light loads (~50% of 1RM) can be used to perform specific dynamic warming up of the muscle groups to be targeted during the training session. However, the aspects mentioned above discussed about warming up are not a rule but could be a direction to promote an increased body temperature and prepare the muscles for exercise training. The choice of exercise type, order and training methods will depend on the general and specific cycle or training phase. Muscle soreness is sometimes reported at the beginning phases of strength training due to unfamiliar stress [71]. The scientific literature still investigates the physiological mechanisms involved in muscle soreness; until the moment, it is believed that muscle soreness is related to muscle cells microscopic tears, resulting in the following symptoms: swelling, pain, inflammation, and reduced function with a peak between 48-72h later exercise, varying from individual to individual being associated with *delayed-onset muscle soreness* (DOMS) [71]. Because of this, the load control should be carried out to promote muscle groups' physical recovery and minimize injuries [60].

5.5 Reference maximal strength (dynamic and isometric exercises) values in several exercises

Tables (2, 3, and 4) show the values of a maximal repetition (1RM) for bench press, squat, and power clean. These reference tables were elaborated through the results obtained by testing 161 Japanese judo university athletes. According to the tests' load, the classifications sought to distinguish the athletes into categories: very weak, weak, average, good, and very good [75]. Physical trainers can use these values to classify athletes of other combat sports, e.g., Olympic wrestling, since the modality is like judo in terms of physical and physiological demands. Table 2 shows the values of 1 RM for the bench press exercise, as described by Aruga et al. [75].

Table 2: One repetition-maximum (1 RM) for bench-press (kg) test of Japanese judo athletes of different weight categories (Aruga et al. [75]).

Category	Very poor	Poor	Regular	Good	Excellent
<60 kg	≤85.0	87.5-90.0	92.5-97.5	100.0-105.0	≥107.5
<66 kg	≤87.5	90.0-97.5	100.0-115.0	117.5-125.0	≥127.5
<73 kg	≤90.0	92.5-100.0	102.5-117.5	120.0-127.5	≥130.0
<81 kg	≤92.5	95.0-105.0	105.0-120.0	122.5-132.5	≥135.0
<90 kg	≤95.0	97.5-107.5	110.0-122.5	125.0-135.0	≥137.5
<100 kg	≤97.5	100.0-110.0	112.5-125.0	125.5-137.5	≥140.0
>100 kg	≤100.0	102.5-120.0	122.5-145.0	147.5-165.0	≥167.5

Table 3 presents the 1 RM squat values of Japanese judo athletes of different weight categories (Aruga et al. [75]).

Table 3: One repetition-maximum (1 RM) for squat (kg) test of Japanese judo athletes of different weight categories (Aruga et al. [75]).

Category	Very poor	Poor	Regular	Good	Excellent
<60 kg	≤102.5	105.0-117.5	120.0-135.0	137.5-152.5	≥155.0
<66 kg	≤107.5	110.0-122.5	125.0-142.5	145.0-157.5	≥160.0
<73 kg	≤110.0	112.5-125.0	127.5-145.0	147.5-160.0	≥162.5
<81 kg	≤112.5	115.0-127.5	130.0-150.0	152.5-165.0	≥167.5
<90 kg	≤115.0	117.5-132.5	135.0-165.0	167.5-185.0	≥187.5
<100 kg	≤117.5	120.0-140.0	142.5-172.5	180.0-200.0	≥202.5
>100 kg	≤127.5	130.0-165.0	167.5-200.0	202.5-235.0	≥237.5

Table 4 shows the values of a 1RM for the power clean exercise, as described by Aruga et al. [75].

Table 4: One repetition-maximum (1 RM) for power clean (kg) test of Japanese judo athletes of different weight categories (Aruga et al. [75]).

Category	Very poor	Poor	Regular	Good	Excellent
<60 kg	≤57.5	60.0-65.0	67.5-72.5	75.0-80.0	≥82.5
<66 kg	≤60.0	62.5-70.0	72.5-82.5	85.0-92.5	≥95.0
<73 kg	≤62.5	65.0-72.5	75.0-85.0	87.5-95.0	≥97.5
<81 kg	≤67.5	70.0-80.0	82.5-92.5	95.0-105.0	≥107.5
<90 kg	≤70.0	72.5-82.5	85.0-95.0	97.5-107.5	≥110.0
<100 kg	≤72.5	75.0-85.0	87.5-97.5	100.0-110.0	≥112.5
>100 kg	≤75.0	77.5-87.5	90.0-102.5	105.0-115.0	≥117.5

Table 5 shows the values of a 1RM for the bench-press exercise in combat sports athletes in different studies.

Table 5: One repetition-maximum (1 RM) for bench-press in different combat sports studies.

Sample	Load (kg)	Author
Wrestling		
Iranian 4x world champion Greco-Roman style (-55kg)	85.00	Mirzaei et al. [76]
Junior Greco-Roman Olympic wrestling Polish team (n=46)	93 ± 19	Starosta et al. [77]
Junior Greco-Roman Olympic wrestling Polish team (n=61)	108 ± 23	Starosta et al. [77]
Brazilian jiu-jitsu		
State-level jiu-jitsu athletes (n=20)	86 ± 18	Costa et al. [78]
State-level jiu-jitsu athletes (n=20)	78 ± 18*	Costa et al. [78]
Judo		
Canadian judo team (n=22)	100 ± 21	Thomas et al. [79]
High-level Finnish judo athletes (n=7)	96 ± 20	Fagerlund and Hakkinen [80]
National level Finnish judo athletes (n=7)	96 ± 12	Fagerlund and Hakkinen [80]
Recreational Finnish judo athletes (n=7)	87 ± 20	Fagerlund and Hakkinen [80]
Brazilian men's team (2002) holders (n=7)	110 ± 25	Franchini et al. [81]
Brazilian men's team (2002) reserves (n=13)	110 ± 23	Franchini et al. [82]
Italian men's Olympic team (2004) (n=6)	160 ± 30	Sbriccoli et al. [82]
Italian women's Olympic team (2004) (n=6)	74 ± 13	Sbriccoli et al. [82]
National level judo athletes	102 ± 10**	Branco et al. [83]
MMA		
Regional level athletes (n=8)	76 ± 11	Del Vecchio and Ferreira [84]
North-American MMA athletes (n=11)	93 ± 8	Schick et al. [85]
Karate		
Brazilian karate team - winners	76 ± 17	Roschel et al. [86]
Brazilian karate team - losers	70 ± 11	Roschel et al. [86]
High-level Japanese athletes (n=7)	87 ± 12	Imamura et al. [87]
Beginner Japanese athletes (n=9)	74 ± 7	Imamura et al. [87]
Brazilian high-level athletes (n=9)	89 ± 19	Loturco et al. [9]
Taekwondo		
Experienced athletes (n=7)	84 ± 24	Toskovic et al. [88]
Beginner athletes (n=7)	86 ± 27	Toskovic et al. [88]
Female experienced athletes (n=7)	37 ± 13	Toskovic et al. [88]
Female beginner athletes (n=7)	36 ± 8	Toskovic et al. [88]
Croatian women's team - medalists (n=6)	56 ± 12***	Markovic et al. [89]
Croatian women's team - medalists – non-medalists (n=6)	48 ± 8***	Markovic et al. [89]

Note: the data are expressed as the mean ± standard deviation; * = test performed stretching before the one-maximum repetition test; ** = unpublished data; *** = test performed with dumbbells.

Table 6 shows the values of a 1RM for squat exercise in combat sports athletes in different studies.

Table 6: One repetition-maximum (1 RM) for squat in different combat sports studies.

Sample	Load (kg)	Author
Wrestling		
Iranian 4x world champion Greco-Roman style (-55kg)	112	Mirzaei et al. [76]
Junior Greco-Roman Olympic wrestling Polish team (n = 46)	112 ± 22	Starosta et al. [77]
Junior Greco-Roman Olympic wrestling Polish team (n = 61)	117 ± 30	Starosta et al. [77]
Judo		
National level Finnish judo athletes (n = 7)	185 ± 25	Fagerlund and Hakkinen [80]
National level Finnish judo athletes (n = 7)	166 ± 32	Fagerlund and Hakkinen [80]
Recreational Finnish judo athletes (n = 7)	140 ± 36	Fagerlund and Hakkinen [80]
Brazilian women's team (2002) holders (n = 7)	104 ± 27	Franchini et al. [81]
Brazilian women's team (2002) reserves (n = 13)	104 ± 18	Franchini et al. [81]
State-level athletes (n = 8)	129 ± 13*	Branco et al. [83]
MMA		
North-American MMA athletes (n=11)	108 ± 8	Schick et al. [85]
Karate		
Brazilian karate team - winners	113 ± 15	Roschel et al. [86]
Brazilian karate team - losers	129 ± 20	Roschel et al. [86]
High-level Japanese athletes (n = 7)	137 ± 12	Imamura et al. [87]
Beginner Japanese athletes (n = 9)	120 ± 13	Imamura et al. [87]
High-level Brazilian athletes (n = 9)	201 ± 31**	Loturco et al. [9]
Taekwondo		
Croatian women's team - medalists (n = 6)	89 ± 18	Markovic et al. [89]
Croatian women's team - medalists – non-medalists (n = 6)	72 ± 15	Markovic et al. [89]
Brazilian team - losers	129 ± 20	Roschel et al. [86]

Note: the data are expressed as the mean ± standard deviation; * = unpublished data; ** = test conducted in the smith machine.

Table 7 shows the values of a 1 RM for power clean, snatch and row exercises in combat sports athletes in different studies.

Table 7: One repetition-maximum (1 RM) for power clean, snatch, and row in different combat sports studies.

Sample	Load (kg)	Author
Power clean:		
North-American wrestling athletes (n = 10)		Schmidt et al. [90]
Early season	79 ± 15	
Half the season	76 ± 15	
End of season	80 ± 14	
Snatch:		
Junior Greco-Roman Olympic wrestling Polish team (n=46)	58 ± 8	Starosta et al. [77]
Junior Greco-Roman Olympic wrestling Polish team (n = 61)	63 ± 13	Starosta et al. [77]
Row		
Brazilian men's team (2002) holders (n=7)	116 ± 21	Franchini et al. [81]
Brazilian men's team (2002) holders (2002) reserves (n = 13)	115 ± 24	Franchini et al. [81]
State level judo athletes (n = 8)	104 ± 11*	Branco et al. [83]

Note: the data are expressed as the mean ± standard deviation; * = unpublished data.

Table 8 shows the maximum repetition (1RM) values for leg-press, deadlift, and leg curl exercises in combat sports athletes in different studies.

Table 8: One repetition-maximum (1 RM) for deadlift and leg curl in different combat sports studies.

Sample	Load (kg)	Author
Deadlift		
Italian Olympic judo team (2004)		
Males (n=6)	127 ± 11	Sbriccoli et al. [82]
Females (n=5)	94 ± 6	Sbriccoli et al. [82]
Leg curl		
Italian Olympic judo team (2004)		
Males (n=6)	77 ± 4	Sbriccoli et al. [82]
Females (n=5)	40 ± 4	Sbriccoli et al. [82]

Note: the data are expressed as the mean ± standard deviation.

Table 9 presents the maximal isometric handgrip strength in combat sports athletes in different studies.

Table 9: Maximal isometric handgrip strength in different combat sports studies.

Sample	MIHS-R (kgf)	MIHR-L (kgf)	Author
Judo			
Brazilian athletes (n=84)			Brito et al. [78]
Right-handed	58 ± 12	53 ± 11	
Left-handed	54 ± 11	56 ± 10	
Brazilian cadet-athletes (n=8)			Franchini et al. [55]
Before training periodization	38 ± 6	38 ± 5	
After training periodization	47 ± 7	44 ± 7	
Brazilian athletes			Franchini et al. [91]
Elite (n=26)	51 ± 10	49 ± 10	
Non-elite (n=66)	42 ± 11	40 ± 10	
Brazilian University team 2000 (n=13)	54 ± 8	53 ± 7	Franchini et al. [91]
Experienced Brazilian judo athletes			Franchini et al. [63]
Before linear protocol	51 ± 8	50 ± 8	
After linear protocol	54 ± 7	54 ± 8	
Before undulating protocol	49 ± 6	50 ± 7	
After undulating protocol	50.5 ± 5	52 ± 6	
Jiu-Jitsu			
Experienced athletes (n=14)	52 ± 12	51 ± 12	Silva et al. [92]
Beginner athletes (n=14)	47 ± 6	47 ± 6	Silva et al. [92]
Experienced athletes (n=50)	50 ± 9	47 ± 9	Oliveira et al. [93]
International level athletes (n=11)	44 ± 5	40 ± 4	Andreato et al. [14]
Athletes – different competitive levels (n=35)	46 ± 10	44 ± 11	Andreato et al. [50]
Blue-belt athletes (n=12)	38 ± 6 (dom. hand)	32 ± 6 (dom. hand)	Andreato et al. [51]
Experienced athletes (n=10)	49 ± 6 (dom. hand)	47 ± 6 (dom. hand)	Andreato et al. [49]
Experienced athletes (n=10)	53 ± 6 (dom. hand)	50 ± 9 (dom. hand)	Andreato et al. [41]
Wresting			
American University Athletes (n=18)	58 ± 13	59 ± 1	Ratamess et al. [94]
Spanish female athletes			Pallares et al. [95]
Experienced athletes (≤ 57 kg; n=6)	31 ± 5 (dom. hand)	30 ± 6 (dom. hand)	
Amateur athletes (≤57 kg; n=7)	27 ± 5 (dom. hand)	26 ± 4 (dom. hand)	
Experienced (≤70 kg; n=7)	35 ± 6 (dom. hand)	34 ± 6 (dom. hand)	
Amateur athletes (≤70 kg; n=10)	33 ± 6 (dom. hand)	30 ± 3 (dom. hand)	

Note: Data are expressed by mean and ± standard deviation; MIHS-R maximal isometric handgrip strength for right hand; MIHR-L = maximal isometric handgrip strength for left hand. dom. hand = dominant-hand

Table 10 presents an option to classify absolute and relative maximal isometric tests for judo athletes of state, national and international level (n = 102).

Table 10: Classification for the absolute and relative maximal isometric tests for male judo athletes based in Branco et al. [96]

	SMIHS		MISHT		MILT		MILBT	
	Absolute (kgf)	Relative (kgf/kg)	Absolute (kgf)	Relative (kgf/kg)	Absolute (kgf)	Relative (kgf/kg)	Absolute (kgf)	Relative (kgf/kg)
Very poor	≤ 76	≤ 0.81	≤ 31	≤ 0.34	≤ 109	≤ 1.14	≤ 110	≤ 1.15
Poor	77-83	0.82-0.96	32-35	0.35-0.41	110-123	1.15-1.41	111-130	1.16-144
Regular	84-111	0.97-1.51	36-47	0.42-0.62	124-167	1.42-2.0	131-169	1.45-2.15
Good	112-133	1.52-1.79	48-49	0.63-0.73	168-169	2.1-2.5	≥ 170	2.16-2.62
Excellent	≥ 134	≥ 1.80	≥ 50	≥ 0.74	≥ 170	≥ 2.6	≥ 170	≥ 2.63

Note: SMIHS = sum of maximal isometric handgrip strength (right and left hand); MISHT = maximal isometric scapular humeral traction; MILT = maximal isometric lumbar traction; MILBT = maximal isometric lower body traction.

The maximal isometric handgrip strength is frequently measured three times for each hand, alternately, with a 1 min interval between attempts. Athletes are instructed to stay in a standing position, with fully extended elbow and self-selected wrist positions. They are encouraged to produce the greatest possible force during 3–5 s, and measurements are conducted using a dynamometer. Absolute and relative to body mass highest values are registered and considered [97,98]. Therefore, coaches and strength and conditioning professionals with access to a handgrip dynamometer and interested in the maximal isometric handgrip strength can also classify their male adult judo athletes (Table 11) [97]. Table 12 shows maximal isometric handgrip strength from different weight categories based in Franchini et al. [97].

Table 11: Maximal isometric handgrip strength classificatory table for male adult judo athletes (n = 406) based in Franchini et al. [97].

	SMIHS		Left hand		Right hand	
	Absolute (kgf)	Relative (kgf/kg)	Absolute (kgf)	Relative (kgf/kg)	Absolute (kgf)	Relative (kgf/kg)
Very poor	≤ 71	≤ 0.92	≤ 36	≤ 0.45	≤ 36	≤ 0.47
Poor	71-85	0.92-1.10	36-41	0.45-0.54	36-43	0.47-0.55
Regular	86-115	1.11-1.48	42-57	0.55-0.73	44-58	0.56-0.75
Good	116-132	1.49-1.68	58-66	0.74-0.85	59-66	0.76-0.84
Excellent	≥ 132	≥ 1.68	≥ 66	≥ 0.85	≥ 66	≥ 0.84

Note: SMIHS = sum of maximal isometric handgrip strength between right and left hand.

Table 12: Maximal isometric handgrip strength for male adult judo athletes from different weight categories based in Franchini et al. [97].

	Right hand		Left hand		Sum	
	Absolute (kgf)	Relative (kgf/kg)	Absolute (kgf)	Relative (kgf/kg)	Absolute (kgf)	Relative (kgf/kg)
60 kg (n = 69)	43 ± 7 [a,b,c,d,e,f]	0.73 ± 0.12 [c,d,e,f]	42 ± 8 [a,b,c,d,e,f]	0.70 ± 0.13 [c,d,e,f]	85 ± 15 [a,b,c,d,e,f]	1.43 ± 0.24 [c,d,e,f]
66 kg (n = 73)	48 ± 6 [c,d,e,f]	0.71 ± 0.09 [c,d,e,f]	47 ± 6 [c,d,e,f]	0.70 ± 0.09 [c,d,e,f]	95 ± 11 [c,d,e,f]	1.41 ± 0.07 [c,d,e,f]
73 kg (n = 83)	51 ± 8 [d,f]	0.68 ± 0.11 [d,e,f]	50 ± 8 [d,f]	0.66 ± 0.11 [e,f]	101 ± 16 [d,f]	1.34 ± 0.22 [d,e,f]
81 kg (n = 70)	54 ± 7 [f]	0.65 ± 0.09 [e,f]	52 ± 7 [f]	0.64 ± 0.08 [e,f]	106 ± 13 [f]	1.29 ± 0.16 [e,f]
90 kg (n = 52)	56 ± 8	0.62 ± 0.09 [f]	55 ± 9	0.61 ± 0.10 [f]	111 ± 17	1.23 ± 0.19 [f]
100 kg (n = 29)	56 ± 8	0.56 ± 0.08	54 ± 8 [f]	0.54 ± 0.08	110 ± 15	1.10 ± 0.15
> 100 kg (n = 30)	61 ± 11	0.49 ± 0.09	60 ± 11	0.49 ± 0.09	121 ± 20	0.98 ± 0.17

Note: the values are presented as mean ± standard deviation; kgf = kilogram-force; a = different form 66 kg (p<0.05); b = different from 73 kg (p<0.05); c = different form 81 kg (p<0.05); d = different from 90 kg (p<0.05); e = different from 100 kg (p<0.05); f = different from > 100 kg (p<0.05).

Table 13 shows the maximal isometric handgrip strength for male judo athletes from different age groups based in Franchini et al. [98].

Table 13: Maximal isometric handgrip strength for male judo athletes from different age groups based in Franchini et al. [98].

	Right hand		Left hand		Sum	
	Absolute (kgf)	**Relative (kgf/kg)**	**Absolute (kgf)**	**Relative (kgf/kg)**	**Absolute (kgf)**	**Relative (kgf/kg)**
Cadet (n = 58)	41 ± 11[a,b,c,d,e]	0.64 ± 0.13	40 ± 11[a,b,c,d,e]	0.62 ± 0.14	81 ± 22 [a,b,c,d,e]	1.25 ± 0.26
Junior (n = 113)	51 ± 9	0.67 ± 0.11	49 ± 10	0.64 ± 0.11	99 ± 19	1.31 ± 0.22
Senior (n = 220)	51 ± 10	0.65 ± 0.11	50 ± 10	0.64 ± 0.12	102 ± 19	1.29 ± 0.22
Master 30-39 years (n = 108)	53 ± 8	0.64 ± 0.14	54 ± 8[a,b]	0.65 ± 0.14	107 ± 16[a]	1.29 ± 0.27
Master 40-49 years (n = 31)	50 ± 8	0.63 ± 0.11	54 ± 8	0.68 ± 0.14	104 ± 14	1.31 ± 0.23
Master 50-59 years (n = 16)	51 ± 7	0.64 ± 0.09	54 ± 6	0.68 ± 0.11	105 ± 12	1.32 ± 0.18

Note: the values are presented as mean ± standard deviation; kgf = kilogram-force; a = different from junior ($p<0.05$); b = different from senior ($p<0.05$); c = different from master 30-39 ($p<0.05$); d = different from master 40-49 ($p<0.05$); e = different from master 50-59 ($p<0.05$).

6. Training prescription

Training sessions that involve 1 to 5 repetitions of 90 to 100% of 1 RM are indicated for a maximal strength increase and can be a relevant strategy for athletes who are at the limit of their respective weight categories, as this method is not associated with an increased muscle cross-sectional area (hypertrophy). However, when the athlete is below the limit of their respective category, the performance of 8 to 12 repetitions between 60 to 85% of 1 RM is recommended to obtain hypertrophy, increasing the cross-sectional muscle area [1,19,99,100]. It is worth mentioning that the work of maximal strength and muscle hypertrophy must be performed on a stable surface, i.e., on the ground, benches, or appliances. Considering that instability leads to an increase in the work of the antagonist muscles, a decrease in strength production, and a lower activation of the muscles that perform the movement/exercise are not a desired training goal [101].

Working with free weights and bars is more suitable for athletes' training. These exercises' execution involves multi-articular actions requiring greater motor coordination, stabilizing and synergistic muscle actions, and developing inter and intramuscular coordination [99]. We highlight several limitations regarding the exercises conducted in machines: limiting the exercises' amplitude and smaller muscles' restricted work, restricting stabilizing and synergistic muscles. However, the machines may be used when there is a need to isolate specific muscles and rehabilitation processes and correct muscular imbalance [99,100].

In turn, Franchini and Del Vecchio [11] emphasize that strength training should be directed to the movements, gestures, actions, and movements performed during the matches. Therefore, the training prescription should be required for each specific athlete to correct any shortcomings, i.e., the “weaker” muscles' work to improve performance during training and competitions.

Besides, strength training may help increase muscle strength, increase total body mass (when possible), reduce the risk of sports injuries, and strengthen core muscles, e.g., rectus abdominal, transverse abdominal, internal and external abdominal obliques, as well as lumbar and gluteus muscles. However, the transfer of non-specific strength training to athletic performance may be limited to athletes. Therefore, training should be as specific as possible, especially about the pattern of movement and speed of muscle contraction to improve inter-muscle coordination and muscle synchronization with the required movement pattern in the modality [102].

6.1 Considerations for training muscle hypertrophy

According to Kraemer [103], muscle hypertrophy is a complex physiological, biochemical, and immunological process related to the repair and remodeling of muscle fibers' different mechanisms. Moreover, during resistance training, the muscle fibers are stimulated by motor units´ recruitment. The same author points out that muscle mass growth is associated with muscle tissue damage resulting from external stimulus, following inflammation and actions of cytokines and other immune cells' responses. Muscle hypertrophy occurs by increasing protein synthesis and decreasing protein breakage. Thus, a positive protein balance promotes muscular hypertrophy [33]. It is essential to highlight that protein synthesis is related to the level of training of athletes/practitioners, i.e., a higher level of training results in less muscle damage caused by the exercise. Scientific evidence has also indicated that protein synthesis begins 4 hours after training in muscle hypertrophy [1]; nonetheless, 16 training sessions for each muscle group, on average, are necessary so that the results are detectable [104]. Nevertheless, for more satisfactory results, training directed to hypertrophy must be maintained for more than 8 uninterrupted weeks [27]. Thus, the main recommendations for the training conducted to muscle hypertrophy to be more effective are as follows:

The performance of exercises that include large muscle masses (Olympic weightlifting exercises, squat, deadlift, row, and bench press, among others) at the beginning of the training; as these exercises stimulate acute increases in the total circulating testosterone concentrations and because the training of smaller muscle groups at the beginning of training may result in a decreased performance in exercises with large muscle groups [27]. Another justification for this order is that multi-articular exercises require more neural demand and more intense, resulting in greater total energy expenditure than smaller exercises performed isolated [33]. Besides, exercising larger muscle groups first provides greater stimulation for all muscles involved in training and may provide a greater potential for remodeling the muscle tissue [70];

The control of the recovery time (pause) between sets and exercises should be continuously monitored for performance maintenance [105] (if it is the purpose of training), as well as for maximizing hormonal responses during training. As a result, research has indicated that pauses less than 60 s favored lactate accumulation, associated with increased growth hormone secretion (GH) after training sessions [70,106–110].

Studies have also indicated that the pause of 60 s between sets tripled GH release after 30 min of training [108]. Moreover, a break of less than 120 s between sets was more effective for testosterone release during strength training [108,112]. Scientific evidence has shown that shorter intervals (less than 60 s) are more useful for anabolic promotion during training sessions directed to muscle hypertrophy [111];

Endocrine responses (hormone release) to hypertrophy training are dependent on the number of sets, repetitions, intervals, exercises, and muscle groups involved in the training [109,112,113]. Therefore, the training session should not exceed 1 hour since longer sessions can minimize the strength gain [114];

The rest interval of 48 hours for the same muscular group should be incorporated since this period is needed to repair and grow the contractile proteins. Thus, two or three weekly sessions per muscle group are satisfactory for the muscle hypertrophy development [115];

The incorporation of the eccentric work is relevant since, in this type of movement, there is an increase in muscular micro-damage incidence, which after the recovery period favors the increase of muscular hypertrophy [116]. Thus, incorporating strategies to increase the overload during the eccentric phase may be used to maximize muscle demand and favor eccentric work;

The training programs must be continuously modified to avoid stagnation of the stimuli resulting from training; that is, every 2-3 weeks of uninterrupted training, the stimuli must be changed [11];

The use of exercises for the same muscle group that contemplates different portions of the same musculature should be proposed for the recruitment and activation of available contractile tissue [1];

External aid can be an essential tool to overcome the point of greatest mechanical limitation in certain exercises, for example, the initial concentric phase of the bench press or arm-curl [117];

The addition of 2 to 10% of the total exercise load when the practitioner or athlete can perform one or two repetitions above the established load should be considered [70];

While detraining, the human body maintains part of the muscle hypertrophy program's adaptation for up to 32 weeks [1].

In the professional intervention, several training models are used to promote hypertrophy, such as: pyramidal, super-slow, paired-set, accentuated eccentric, pre-exhaustion, rest-pause, drop-set, among others [118]. According to these authors, the scientific literature does not show significant muscle hypertrophy differences between training methods. The same research group published an experimental study comparing the effects of crescent pyramid, drop-set systems, and traditional resistance training equalized by total training volume on physical and physiological variables in well-trained men [119]. The following variables were analyzed before and after 12 training weeks: 1 RM, cross-sectional muscle area (CSA), pennation angle (PA), and fascicle length (FL). The results showed a leg-press 1 RM improvement: for crescent pyramid with 16.4%, drop set system with 17.1%, and traditional training with 16.6%; a CSA improvement: for crescent pyramid with 7.5%, drop set system with 7.8%, and traditional training with 7.6%; a PA improvement: for crescent pyramid with 11.0%, drop set system with 10.3%, and traditional training with 10.6%; and a FL improvement: for crescent pyramid with 8.9%, drop set system with 9.1%, and traditional training with 8.9%. Thus, the authors concluded that the physical and physiological responses were similar when the total training volume was equalized. These responses suggest that muscle hypertrophy's central point is the total training volume per session and not the training method chosen. In table 14, we present the recommendations for the training directed to promote muscle hypertrophy for different groups according to Wernbom et al. [100].

Table 14: Recommendations for the training directed to promote muscle hypertrophy for different groups according to the recommendations of Wernbom et al. [100].

	Moderate load slow-speed training	Conventional hypertrophy training	Eccentric (ecc) overload training
Muscle action	Concentric and eccentric	Concentric and eccentric	Eccentric (concentric = optional)
Exercise	Single and/or multiple joint	Single and/or multiple joint	Single and/or multiple joint
Load	~50% of 1RM	8-10 RM (range 6-12) ~75-80% of 1RM	Eccentric = > 105% of 1RM Concentric = 60-75% of 1RM
Repetitions	8-14 to muscular failure	8-10 to muscular failure or near	4-6
Sets	1-3 per exercise. Progression from 1 to 3-4 sets in total per muscle group	Progression from 1-2 to 3-6 sets in total per muscle group	Progression from 1-2 to 3-5 sets in total per muscle group
Velocity and duration per repetition	Slow Eccentric = 2-3 seconds Concentric = 2-3 seconds	Moderate Eccentric = 1-2 seconds Concentric = 1-2 seconds	Slow/moderate Eccentric = 2-4 seconds Concentric = 1-2 seconds
Rest between sets	30-60 seconds	60-180 seconds	120-180 seconds
Frequency	2-3 sessions per muscle group/week	2-3 sessions per muscle group/week	1-3 sessions per muscle group/week
Comments	Suitable training method for beginners and individuals who cannot tolerate high forces	These recommendations are for novice to moderately trained individuals. Well trained athletes may need increased variation in intensity and volume	Mainly for advanced to elite athletes. Progressive but careful increase of the load and volume for the eccentric phase

The training programs must be continuously modified to avoid stagnation of the stimuli resulting from training; that is, every 2-3 weeks of uninterrupted training, the stimuli must be changed [11];

6.2 Considerations for maximal strength training

Recommendations for maximal strength training should be directed at individuals at the upper limit of their respective weight categories. Thus, the primary suggestions for maximum strength training to be more effective are as follows:

Maximal strength training for the beginner or untrained practitioners should be performed 2-3 times a week on alternate days [33,114,115];

For moderately trained practitioners, training is indicated 3-4 times a week, with a greater volume, intensity, and diversity of exercises than those for beginners or non-trained [33,115];

For athletes, each muscle group should be worked, on average, twice per week, with a greater volume and intensity than for moderately trained practitioners. Emphasis should be placed on the exercises related to the specificity of the combat sport [11];

The period of the training session should be approximately 45-60 min [114];

From a physiological point of view, the optimal recovery time between sets should be 3-5 min [110]; however, authors suggest the adoption of 5-8 min for complete recovery in multi-articular exercises, such as Olympic weightlifting exercises [120];

Strategies such as using the circuit training method may reduce the session time to enable an ideal training volume [120]. Also, the circuit training method promoted increased activation of the cardiovascular system (71% of maximal heart rate), while the conventional strength training method promoted lower cardiovascular activation (62% of maximum heart rate) [121];

The use of 3 to 6 sets of 3-5 rep with loads equal to or greater than 85% of 1 RM are indicated for maximum strength training [122], and evidence also suggests that percentages between 90 and 95% of 1 RM can be used for maximum strength development [123]. The inclusion of training with 100% of 1 RM is also indicated, but to a lesser extent, and is dependent on the periodization model adopted [1,114];

The interval between training sessions for the trained muscle groups should be 72 hours [105];

External aid should be a valuable tool to overcome the point of greatest mechanical limitation, particularly in maximal strength exercises [117];

As discussed in the topic of muscular hypertrophy, exercises of large muscle groups should be performed at the beginning of the training session because fatigue generated by the activation of several muscles (such as in multi-articular exercises) can jeopardize the safety of its execution [99];

From two weeks of detraining, maximum strength reductions occur in previously untrained individuals (10 to 20%). However, in highly trained athletes, this variation is lower [1] (approximately 5%);

Studies have also indicated that the correct distribution of the training volume in the intensively strength/hypertrophy program, e.g., two daily sessions, can provide better hypertrophy and strength development conditions during short periods of intervention (3 weeks) [103-105,120-123].

6.3 Maximal isometric strength

The maximal isometric strength is angle-dependent; that is, it occurs mainly at the angle that the stimulus is being performed [3,27,104,117]. The maximal isometric strength training may favor the mechanical point of least strength in particular exercises during eccentric and concentric dynamic actions [122-125], especially in very high loads and close to the maximum [126]. Studies have also indicated that isometric strength differs according to exercise angles used [127]. Therefore, isometric actions should be performed at 10 to 20 degrees during the entire exercise range to transfer the dynamic activities [27].

It is recommended to use the following aspects for isometric training [117]: 1) The most vital angles of the exercises or movements should be trained; 2) The repetitions should be performed every 10 or 20º or with the extended muscle; 3) The isometric stimulus is between 3 and 10 s; 4) 15 to 20 actions are performed per training session, and external assistance is indicated for the safe accomplishment of isometric training [114-116].

Specific isometric exercises should stimulate the demand for each combat sport. For judo and jiu-jitsu, some exercises are indicated, such as handgrip with extended elbow (15 to 20 repetitions of 3 to 5 s at 100%) and support at the bar holding the gi with an external overload to induce fatigue in up to 10 s (following the previous recommendations). In Olympic wrestling, exercises such as the bear hug, using between 15 and 20 repetitions at 100% [120], are recommended for maximal isometric strength training.

7.Exercise prescription for grappling, striking, and mixed martial arts

The following body regions and exercises are indicated for combat sports athletes that can be performed with bars, cables, accessories, and dumbbells simultaneously and unilaterally [1,11,18,22,117,126–138].

- ✓ Multi-articular groups: weight-lifting exercises, such as power clean, hang clean, clean and jerk, jump shrug, snatch, military press, push-press;
- ✓ Back: bent-over row, pull-ups, seated high row, lying row, seated high row, smith bent-over row and straight back;
- ✓ Pectorals: bench press, chest dip, decline chest press and incline bench press;
- ✓ Upper-limbs: arm curl, triceps extension, pulley triceps, and triceps dip.
- ✓ Forearm*: reverse curl, barbell wrist curl, cable roller wrist flexion, kimono or judogi chin-up (isometric and/or exercises with overload) * = exercises indicated for the grappling combat sports and MMA;
- ✓ Erectors of the spine: good morning, barbell deadlift, Romanian deadlift and barbell back extension (on hyperextension apparatus);
- ✓ Anterior thigh: front and back squat, half-squat, lunges, lateral lunges, leg-press, and leg extension.
- ✓ Back of thigh: stiff, leg curl and leg-press (with angle adjustment);
- ✓ Back of the leg: standing calf raise in the Smith machine;
- ✓ Abdomen: barbell push sit-up or with medicine-ball, weighted crunch, front plank or/and lateral plank;
- ✓ Neck*: neck flexion, neck rotation, weighted lying neck flexion, front neck bridge, wall front neck bridge, and wall side neck bridge; * = grappling modalities and MMA.

The prescription of maximal strength training and muscular hypertrophy can include the characteristics described by Bird et al. [70], i.e., the proper program design needs to consider some points highlighted:

- *Acute program variables:* muscle action, rest periods, loading and volume, repetition velocity, exercise selection and order, and frequency;
- *Key training principles:* overload, specificity, progression, individualization, adaptation, and maintenance.

Specific training outcome:

- *Muscular endurance:* eccentric and concentric exercises, with 1-3 sets x 15-20 RM, using single and multi-joint exercises, varying exercises order, with 30-60 s of rest, and performed 2-3 times a week;

- *Hypertrophy training:* eccentric, concentric, and isometric exercises, with 4-6 sets x 8-15 RM, using single and multi-joint exercises, large to small muscle groups, with 1-2 min of rest, and conducted 3-5 times a week;
- *Maximal strength:* eccentric, concentric, and isometric exercises, with 3-5 sets x 1-3 RM, using single and multi-joint exercises, large to small muscle groups, with 3-5 min of rest, and performed 3-5 times a week;
- *Power training:* eccentric and concentric exercises, 3-5 sets x 6-8 RM, multi-joint exercises, large to small muscle groups, with 5-8 min of rest, and performed 4-6 times a week. The training details about muscular endurance and power training are discussed in the specific chapters about these contents.

8. Final consideration

It is important to emphasize that maximum strength training is essential for improving the subsequent phases of training periodization or training planning, such as muscle power and strength-endurance. Therefore, maximum strength should be included in the athletes' training process. The method can also be used for athletes in the upper limit of their respective weight categories since it is possible to increase the maximum strength without promoting muscle hypertrophy. Undoubtedly, maximum strength training should be prescribed based on each athlete's characteristics and needs; that is, the biological individuality should be considered and respected. It is emphasized that maximum strength training is established as a viable method to maximize athletes' performance in various sports. Nevertheless, acute and chronic studies that contemplate different strength training methods for combat sports athletes remain incipient. From this perspective, conducting studies seeking to consider different combat sports training methods is critical. Hypertrophy training is also used during training routines, considering the main muscle groups requested during combat in a given weight category, and physical assessment tests' responses (i.e., whether the athlete is above the weight category limit change his/her weight category). Finally, it is emphasized that training and monitoring should be analyzed and incorporated in the training routine based on the athletes and technical commission and staff available resources.

Conflict of interest

None declare.

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CHAPTER 4
Developing muscle power for combat sports athletes

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Abstract
In combat sports, the specificity of the training requires that the athlete improve all performance indicators associated with the match. For this reason, muscle power seems to be determinant during the application of the techniques that result in scores, specifically punches, kicks, elbows, knees, throwing techniques, transitions to the groundwork and some groundwork techniques and sometimes, the win match by knockout. Based in these information's, the present chapter will approach items referring to the muscle power manifestation and monitoring, and to the training prescription of exercises for the grappling, striking and mixed combat sports.

Keywords: Martial arts; combat sports; strength; strength conditioning; strength training.

1. Introduction

In combat sports muscle power seems to be determinant during the application of the techniques that result in scores, specifically punches, kicks, elbows, knees, throwing techniques, transitions to the groundwork and some groundwork techniques. Power is defined as the product of force (mass multiplied by acceleration) divided by velocity (distance/time). Therefore, the increase of any of these components will improve the athlete's performance in this capacity, provided that the others remain constant [1,2]. For example, if the goal is to improve power during the vertical jump, the athlete should be able to: [1] jump higher with the same load over the same time; [2] jump with the same overload in a shorter time; [3] jump with additional load over the same time; or [4] any combination mentioned above. Thus, it is appropriate for the trainer to check in which of these characteristics the athlete has a better chance of improving performance, i.e., whether he/she is more likely to improve in the force or in the velocity component [3].

Knowing that there is a linear and positive relationship between maximal strength and muscle power, athletes will not achieve the highest power level without first reaching higher levels of strength [4,5]. This assertion can be demonstrated by cross-sectional studies that show that stronger individuals manifest more muscle power than the weaker ones [6–9]. It is also known by sports professionals that strength training programs improve the muscle power performance of untrained or moderately trained individuals. However, this influence between strength and muscle power seems to decrease when the athlete is already highly trained in this physical component [10]. This happens because with increased maximum strength the "window for future adaptations" decreases [11]. Therefore, the more trained the athlete is, less trainable he/she will be. This happens because there are biological limits for adapting the body and consequently for the muscle strength and power development [12].

In addition to the influences mentioned above, muscle power is also affected by acute training variables, including the type of exercise, the order in which the exercises are performed, number of sets and repetitions, and the rest interval between sets and repetitions or group of repetitions

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(cluster) [13,14]. Additionally, the training means and methods applied to the combat sports athletes have also been a topic of investigation [15,16]. However, the intensity to be used is the greatest topic of debate concerning the muscle power training prescription. A great variation is observed in the recommendations of the intensity, and in some cases, the variation is between 30-60% of 1 repetition maximum (1RM), whereas in other cases, the recommended loads are around 80% of 1RM [17] and in another cases, it is mentioned that only high loads should be used [18]. The proponents of the use of higher loads (80% of 1RM) are based on the "size principle",' which suggests the application of higher loads for the recruitment of motor units with higher activation threshold, fast twitch muscle fiber type, which generate greater force than the slow twitch muscle fiber type, with lower activation threshold. Muscle power training with this characteristic results in repetitions with slower velocity, however, it has been emphasized that the athlete should have the intention of performing the movement more as fast as possible, even if this is not possible, so that there is an improvement in performance. On the other hand, lighter loads are based on the "specificity principle", in which suggests that the athlete can generate greater muscle power and better adaptations when using the optimal load. A third group advocates the use of loads with greater amplitude, between 10-80% of 1RM. This group assumes that training for the development of muscle power involves the use of several exercises [19,20], which in turn, generate the greatest power at different intensities. For example, during the jump the maximal power is achieved unload whereas the maximum power for the squat, power clean and hang power are achieved with loads of ~50%, 70% and 80% of 1RM, respectively. Values of optimal load for specific combat sports athletes such as Brazilian jiu-jitsu (BJJ) athletes have been determined for exercises frequently used in their training routine [21,22]. The optimal load for bench press throw was around 42% of 1RM for both advanced and non-advanced BJJ [21], whereas for the prone bench pull the optimal load varied between 45% and 50% of 1RM for different power-related variables [22].

Another aspect that deserves attention regarding muscle power training is the possibility of transference and consequent improvement of the performance in specific gestures of the modality practiced, in our case combat sports, by using strength and power exercises [23]. Nowadays, it is not possible to determine in which extent the load that maximizes power output performing a general exercise is related with power in a specific combat sport action. However, it is inferred that the greater the biomechanical similarity of movements and recruitment patterns of muscle fibers, greater the specificity and the possibility of transference of performance [13]. Additionally, multi-articular exercises are more specific and had more possibility of transference in comparison with mono-articular exercises [13]. Recent studies have investigated the acute effect of strength, plyometric and complex exercises on performance in specific taekwondo [16,24–26] and judo tasks [15,27]. The effect of training using specific gestures with overload has also been investigated [28,29].

The understanding of the strength manifestation in the form of muscle power of the athletes is important for the correct elaboration of the training sessions that will compose the training planning. More and more, training programs should be based on scientific evidence and principles, leaving aside beliefs and conceptions that contribute very little to the athlete's development [12,30]. Therefore, this chapter will approach items referring to the muscle power manifestation and monitoring, and to the training prescription for the grappling and striking combat sports.

2. Muscle power solicitation during the match

2.1. Striking combat sports

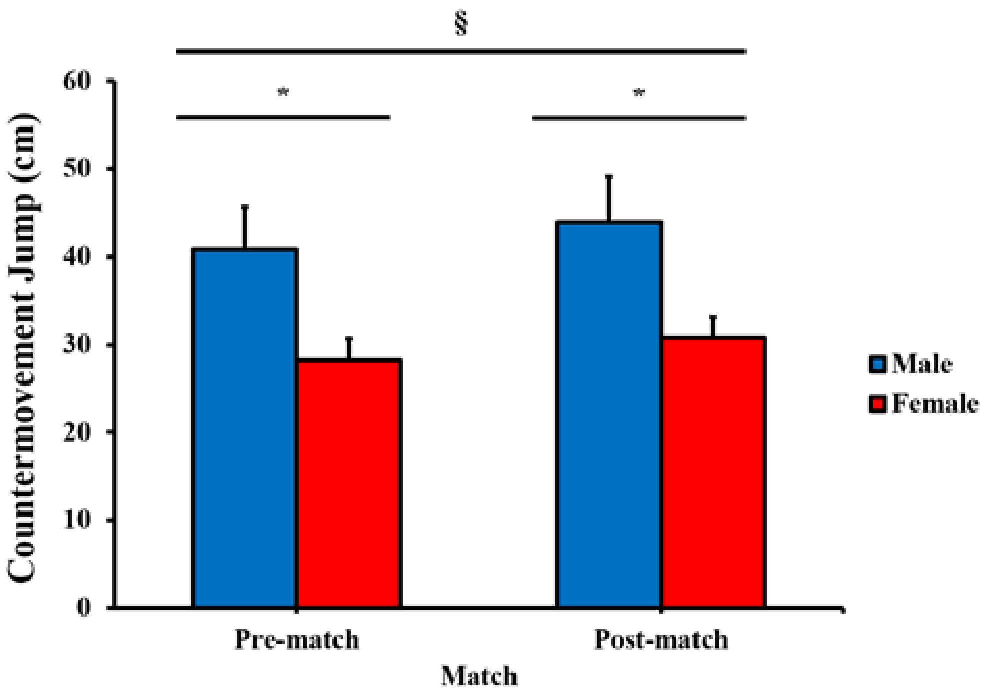
In striking combat sports, muscle power manifests itself mainly at the moment of a technique execution and, during a match, several techniques are applied. Therefore, in addition to the condition to apply blows with these characteristics, the athlete must be able to do this throughout the match. Studies that investigated the time-structure of striking combat sports (taekwondo, karate, muay-thai) presented an effort and pause ratio of 1:6 to 1:9 [31–33]. This relationship was investigated both during competitions and during the match simulation.

In taekwondo competitions, World Taekwondo (WT) style, the effort and pause ratio is ~1:7 [33,34]. During a match simulation, the average time of each attack lasts ~1s [34]. Athletes perform on average 18 attacks per round. The average time spent with attack actions during each round is

~13s. Throughout the match, the athletes perform ~52 attacks, with a total duration of ~39s, as one round lasts 120s and the match lasts 360s. Thus, it is possible to understand that the time intended for the attack represents ~11% of the duration of each round and, consequently, of the total time of the match. During international taekwondo competitions, such as the Olympic Games and the World Championships, the average duration of each attack was 1.3s [33].

In combat sport studies, the power output is widely assessed via indirect tests like vertical jump or countermovement jump (CMJ). It is known that factors such as arm or leg length and body mass can limit the performance and interpretations of the results [13,35]. This is a limitation about combat studies and tests choices, but is important to highlight that combat sport athletes are more homogeneous (because they are well trained and compete in specific weight categories) than the non-athlete population, reducing the bias of the use of jump tests as indirect tools to assess the power output generated.

However, it seems that the muscle power manifestation is not adversely affected during the taekwondo match. A study that aimed to investigate the muscle power manifestation of high-performance taekwondo athletes (15 subjects, 4 females and 11 males) during a national level competition described higher values, as measured by countermovement jump (CMJ) after the match, compared to the measure obtained prior to the match [36]. We can suggest that there was a potentiation of CMJ performance when the pre- and post-match moments were compared, as shown in Figure 1, generated by the stimulus of the match.



Note: § difference between pre- and post-match moments (p <0.001); * difference between the sexes (p <0.001).

Figure 1: Performance during counter-movement jumping performed pre- and post-match by taekwondo athletes of both sexes (Adapted from Chiodo et al. [36]).

Additionally, the muscle power manifestation in striking combat sports may vary during the match simulation in comparison to the official match. Chaabène et al. [37] investigated whether there was a difference in the performance of karate athletes during a simulation compared to an official match. It was observed that athletes applied more attacks using upper limbs during the official competition (6 ± 3) compared to the match simulation (3 ± 1). Concerning the match intensity, higher blood lactate concentrations and rating of perceived exertion were observed after the official match in comparison to the simulation. Thus, the physiological responses may differ considerably between the simulation and the official match, and it is necessary to analyze case by case, considering the combat sport practiced, the competitive level of the athlete and the condition in which the analysis is being performed.

When a top-level karate athlete - double World champion - was analyzed [38], small improvements of 1.1% and 2.9% were observed in the squat jump (SJ) and CMJ performances, respectively, after the combat simulation compared to pre-combat. For jump squat, an increase in power output was detected after the match simulation compared to pre-match, with values varying from 0.6% (when using an additional load of 40% of body mass) up to 7.4% (when the additional load was 80% of body mass). Conversely, for bench press throw a decrease in power output was found after the match compared to pre-match, with values varying from -0.5% (for a load of 30% of body mass) to -8.3% (for a load of 40% of body mass). A decrease in rate of force development (for the period between 0-100ms) was revealed for both half-squat (-3.6%) and bench press (-9.8%) exercises. The increase in jump squat exercise can be a result of a post-activation potentiation (PAP) effect or like named recently as post-activation performance enhancement (PAPE), likely due to the small use of kick techniques during the combat and to the long interval observed between successive kicks. The term PAPE was suggested recently as alternative to PAP and is applied when enhancements of measures of maximal strength, power, and speed are detected following conditioning contractions and PAP when exist an increase in muscular force/torque production during an electrically-evoked twitch) [39,40]. Conversely, as this athlete used frequent punching techniques, the decrease in bench press throw performance likely resulted in fatigue in these muscle groups. However, it is important to consider that even this decrease can have a small negative effect in punching techniques, as lower-body muscle power is a key element for punching power. Consequently, the lower-body post-activation effect observed should counteract the decrease in upper-body muscle power.

Ouergui et al. [41] compared winners and defeated athletes before and after a kickboxing match concerning muscle power variable. Winners and defeated kickboxers did not differ in CMJ. However, decrease was observed for CMJ (pre: 39.3 ± 4.7; post: 35.7 ± 5.0 cm) suggesting that match-induced fatigue impaired muscle power performance.

2.2. Grappling combat sports

In grappling combat sports, muscle power is manifested during throwing techniques and in the attempts to displace the opponent. During the throwing technique execution, the athlete must frequently throw himself/herself to generate very high-power values to be successful to throw his/her opponent. Some studies on the match temporality indicate that the grappling combat sports (judo, BJJ, wrestling) present an effort-pause ratio of 2:1 or 3:1 [42–45].

Two studies that aimed to investigate the effects of the Olympic wrestling competition simulation on vertical jump performance [46,47]. In the first study, conducted with the freestyle, the athletes performed a simulation composed of a total of five matches: three in the first day and two in the second day [47]. As shown in Figure 2, the performance generated after match 1, 2 and pre-match three was higher than that generated in pre-match four.

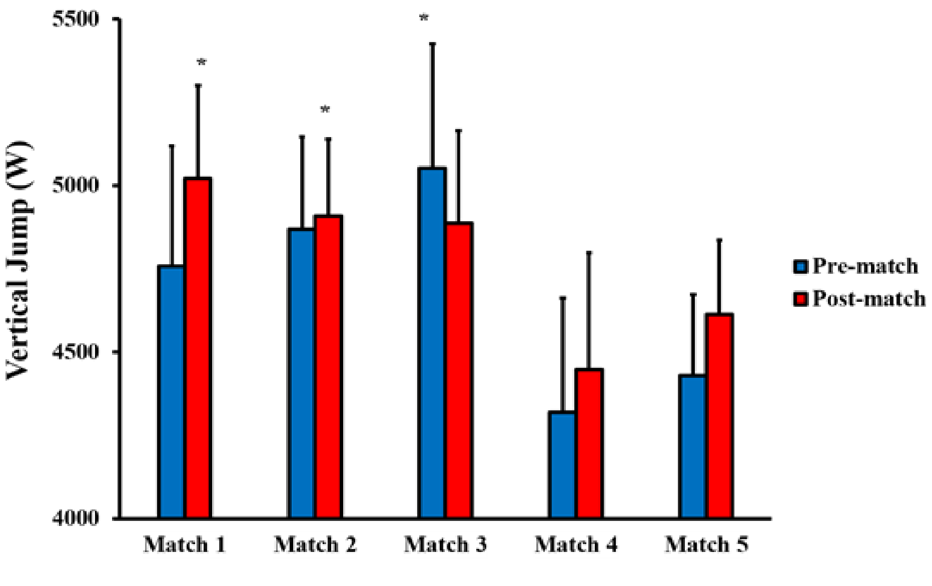
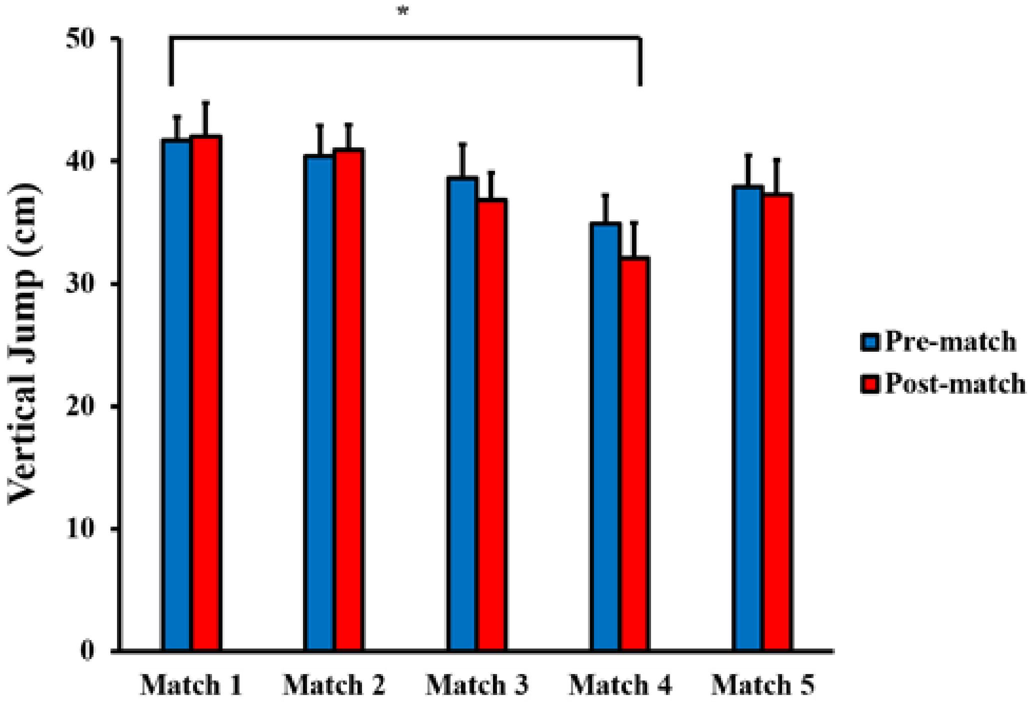


Figure 2: Vertical jump performance performed pre- and post-matches by freestyle wrestlers (Adapted from Kraemer et al. [47]).

Note: * different from the 4th pre-match ($p < 0.05$).

In the second study, conducted with the Greco-Roman style, the five matches were performed in the same day [46]. Before and after each simulation the athletes performed the vertical jump. It was observed a reduction of jump height in the fourth match compared to the first match, as can be observed in Figure 3.



Note: *different from the respective values of the first fight ($p < 0.05$).

Figure 3: Vertical jump performance performed pre- and post-matches by Greco-Roman wrestlers (Adapted from Barbas et al. [46]).

Among judo athletes, no power reduction was observed during a day of competition simulation. Before and after each match the athletes performed the concentric phase of the squat exercise. As can be seen in Figure 4, there was no statistically significant change in performance. Thus, despite trying to associate high blood lactate concentrations with a metabolically unfavourable environment for the muscle power manifestation, there is currently no evidence to confirm this [48,49].

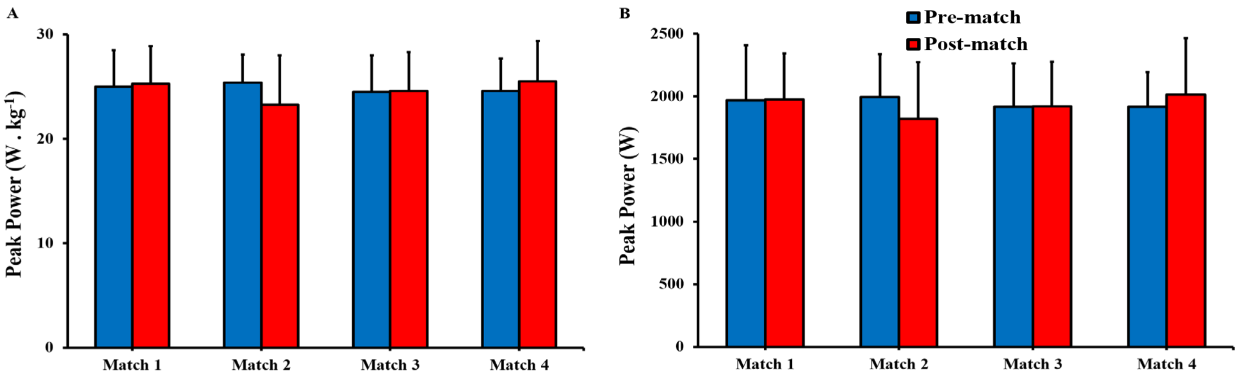
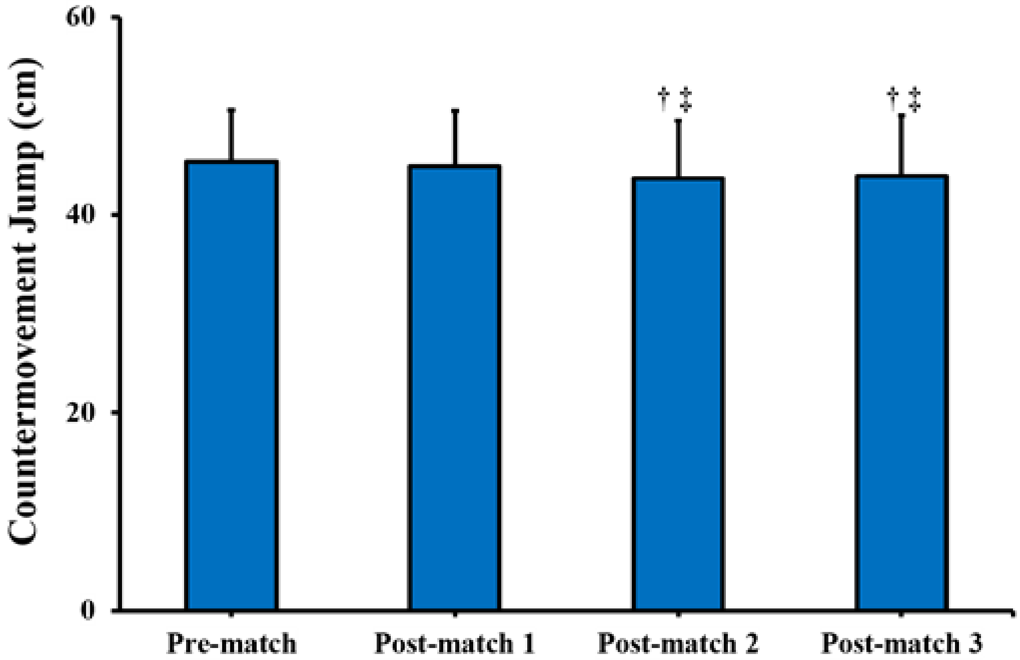


Figure 4: Relative (A) and (B) absolute power generated during the concentric phase of the squat performed pre and post-match by judo athletes (Adapted from Bonitch-Domínguez et al. [48]).

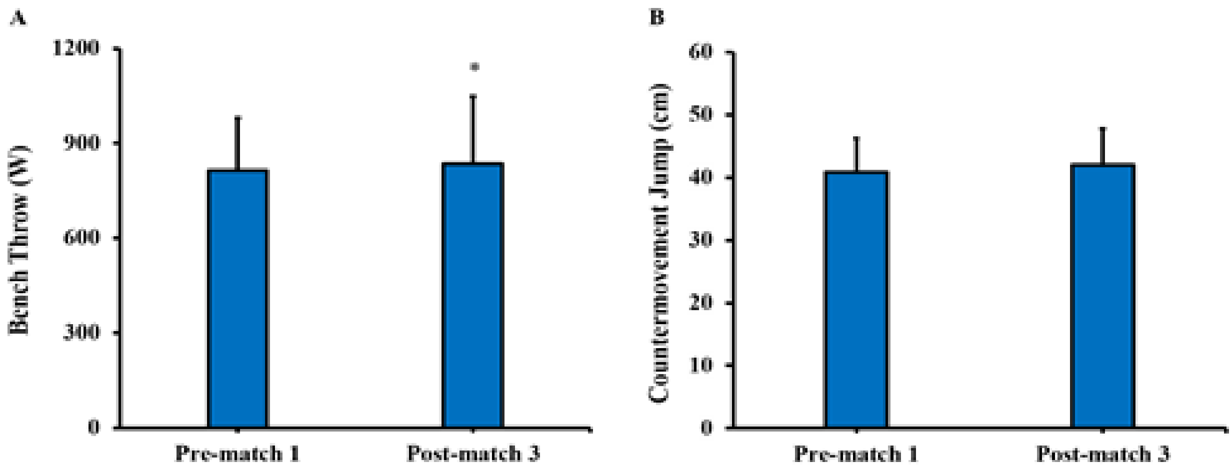
In another study carried out with judo athletes, there was a statistical difference in CMJ height pre-match compared with post second and third matches, and post first match compared with post second and third matches (Figure 5) [50]. The authors mention that the performance drop was ~3%. However, it is worth noting that the authors of this study did not present the coefficient of variation of the athletes for the CMJ test, therefore it is possible to attribute the difference found to the variation of each athlete to the performance of the CMJ.



Note: † different (p <0.05) from the pre-match moment; ‡ different (p <0.05) from post-match moment 1.

Figure 5: Performance in the countermovement jump of judo athletes before and after successive matches (Adapted from Detanico et al. [51]).

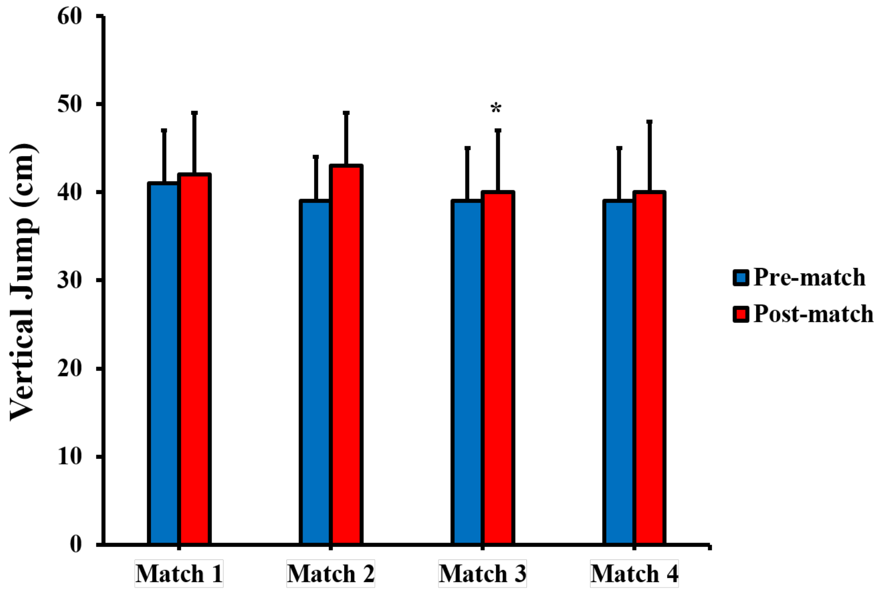
The neuromuscular performance was also investigated among BJJ athletes after successive matches. In one of the studies, the athletes performed three matches with a 15-minutes rest interval between them [49]. The performance tests were applied in two moments, pre-match 1 and post-match 3. As can be seen in Figure 6, there was an improvement in CMJ, but there was no change in ballistic bench press performance.



Note: * different from pre-match 1 (p <0.05).

Figure 6: Performance in the countermovement jump and ballistic bench press performed by Brazilian jiu-jitsu athletes before and after successive matches (Adapted from Silva et al. [49]).

In another study, performed with BJJ athletes, there was a decreased performance in the vertical jump after a match and before the next match [52]. This difference may be a result of the post-activation potentiation generated during match 2 and manifested during the test performed after the end of the match and the return of the performance to the resting values, presented before the match three. This effect is possible since between the end of a match and the beginning of the next the athletes went through a sufficiently long rest so that the effects of the PPA dissipated. Thus, although BJJ is a modality in which athletes perform powerful gestures to throw their opponents, it is possible to affirm that the match, or successive matches carried out on the same day, does not affect or affect positively the muscle power of lower limbs and does not affect the muscle power of upper limbs, as can be observed in Figure 6 (A and B) and 7.



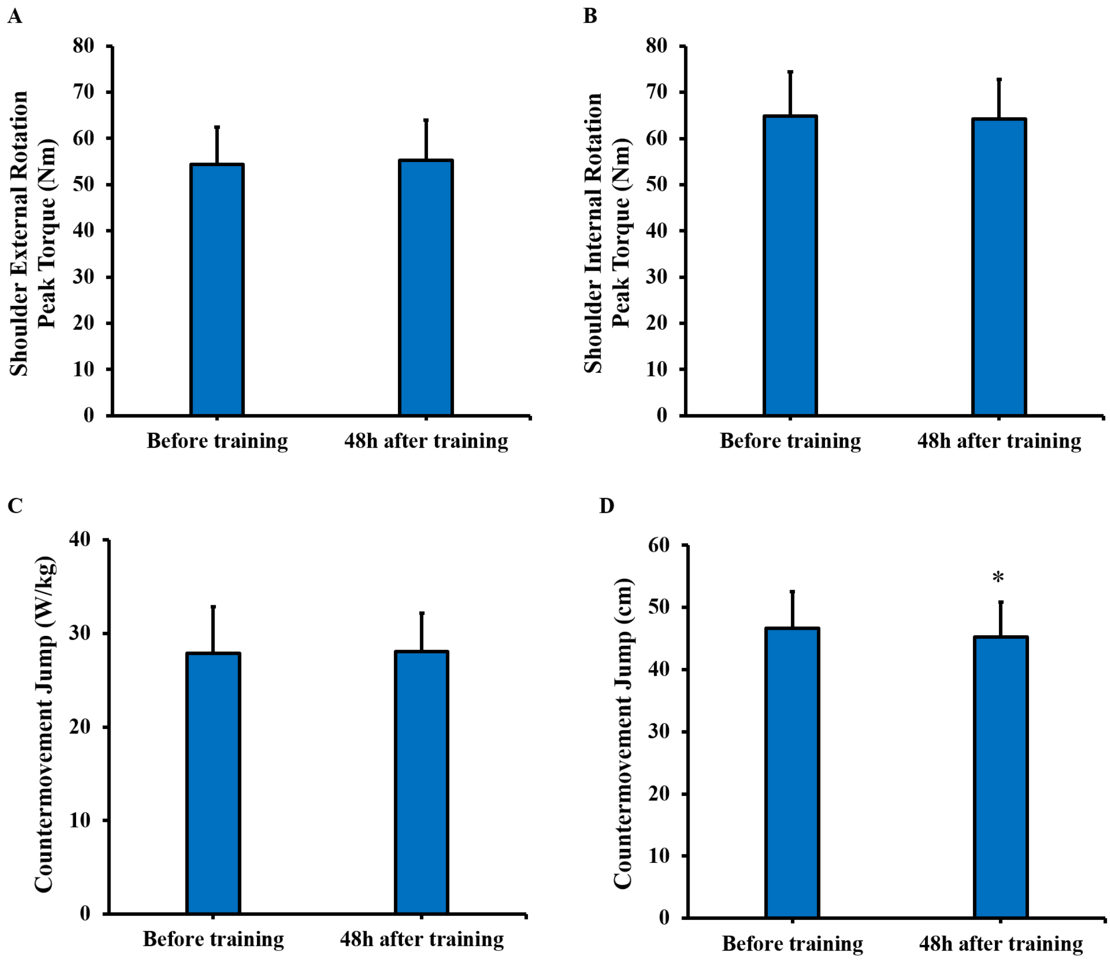
Note: * different from post-match moment 2 (p <0.05).

Figure 7: Vertical jumping performance pre- and post-match Brazilian jiu-jitsu athletes (Adapted from Andreato [52]).

Andreato et al. [53] investigated the effects of different simulated match durations on CMJ performance. These authors reported that CMJ height did not change after matches of 2 min (40 ± 4 cm), 5 min (40 ± 5 cm), 8 min (40 ± 2 cm) and 10 min (41 ± 4 cm) compared to a control condition (39 ± 3 cm). Additionally, CMJ did not differ between the different match durations. Indeed, a non-significant variation of 1 ± 1 cm/min was observed between pre-match and 2-min matches and 0 ± 0 cm/min for matches lasting 5, 8 and 10 min. Therefore, it was concluded that the lower-body overload is small during BJJ matches, which is confirmed by the low report of fatigue for the muscle groups in this segment, and this can explain the absence of decreased lower-body muscle performance along matches with different durations.

In a similar approach, Julio et al. [54] analyzed the effects of different simulated judo match durations (1, 2, 3, 4, or 5 min) on CMJ height, and found increased values post-match compared to pre-match, although no differences were found between matches with different durations. This result was attributed to the high-level of the athletes tested, which may have not developed lower-body fatigue during the matches, and especially due to a post-activation potentiation effect because the tests were executed 7-min post-match, an interval considered optimal for the potentiation to occur [55].

No many studies analyzed the effect of combat sports specific training on muscle power-related variables [56]. This knowledge is quite relevant to improve training organization, as muscle damage and recovery processes affect the subsequent performance, which consequently may impact training adaptation. Detanico et al. [56] investigate the effects of a 90-min typical judo training session on shoulder internal and external rotation peak torque and CMJ height. These variables were measured before the training session and 48 after its completion. They did not observe any change in shoulder rotation external peak torque (Figure 8, part A) or internal peak torque (Figure 8, part B), or CMJ peak power (Figure 8, part C). However, CMJ height decreased after the training session compared to before (Figure 8, part D). The authors considered that as upper-body judo gestures involve mainly concentric and isometric actions and judo athletes are adapted to the judo-specific demand, muscle damage was not elevated. Moreover, to avoid fatigue in such a long session it is likely that the judo athletes executed their actions in a lower intensity than during official matches or isolated simulated matches. Another possibility is that the long recovery period (i.e., 48h) allowed a full recovery and, therefore, no change was observed for shoulder internal and external rotation peak torque. Conversely, the decrease in CMJ height is probably related to the high eccentric-concentric load (i.e., stretch-shortening cycle) during lower-body actions executed in the training session, which can induce muscle damage and performance decrement.



Note: * different from before training (p <0.05).

Figure 8: Neuromuscular parameters of shoulder external and internal rotation torque and vertical jump performance obtained before and 48 hours after the training (Adapted from Detanico et al. [56]).

2.3. Mixed Combat Sports

The muscle power is also manifested in the mixed combat sports during the application of blows and attempts of displacements. The mixed combat sports present an intermediate effort-pause ratio compared to the grappling and striking combat sports, normally around 1:2 to 1:4 [50]. Although we did not find any investigation assessing muscle power changes over a MMA match, it was reported that for MMA athletes, those with high competitive level presented higher relative impulse with additional loads of 0% to 50% of body mass, relative impulse in 300 ms with additional loads of 25% to 100% of body mass, peak power and velocity, mean power and velocity with additional loads 0% to 100% of body mass, peak of rate of force development with additional loads of 0% to 100% of body mass, and mean rate of force development with additional loads of 25% to 100% of body mass during the SP compared with lower level athletes [57]. These results indicate that muscle power is a key variable to properly discriminate higher and lower levels MMA athletes.

3. Muscle power requisition during combat sports-specific situations

During the performance of striking techniques, muscle power has been considered an important parameter for obtaining the knockout or to score [58,59]. Studies with muscle power analysis in specific actions have confirmed this idea. The muscle power during the execution of the straight punches in a dynamometer specifically developed for the boxing was greater in elite boxers with both the rear (4800 ± 601 a.u.) and lead hands (2847 ± 596 a.u.) in relation to intermediate boxers (rear hand = 3722 ± 375 a.u., lead hand = 2283 ± 355 a.u.) and beginners in the modality (rear hand = 2381 ± 328 a.u.; lead hand = 1604 ± 273 a.u.) [58], indicating the importance of this variable in the boxers development or in their selection process.

During throwing techniques, muscle power has also been considered extremely relevant [60–62]. Iteya et al. [61] reported higher power values in the sleeve pull movement in Japanese elite judo athletes in relation to university and regional level athletes. As the pulling movement is important for the opponent's imbalance and can reach values of 3.0 N/kg in the pull of the sleeve and 1.5 N/kg in the pull of the collar [60], the improvement of muscle power for execution of these actions is paramount for the successful execution of throwing techniques. Confirming the relevance of the muscle power during the *kuzushi* (unbalance) phase, Helm et al. [63] reported that elite judo athletes generated higher levels of power in the pulling arm (power = 420.9 ± 49.1 W, 3.9 ± 1.0 W/kg) and lifting arm (power = 246.0 ± 66.3 W, 2.7 ± 0.7 W/kg) during a pulling action in a specific ergometer compared to sub-elite judo athletes (pulling arm power = 245.5 ± 72.7 W, 3.1 ± 0.8 W/kg; lifting arm power = 138.1 ± 82.3 W, 2.1 ± 0.7 W/kg). Additionally, during the execution of the throwing techniques, athletes need high power in the lower limbs [64]. In fact, Zaggelidis, Lazaridis, Malkogiorgos, and Mavrovouniotis [62] reported higher values of vertical ground reaction force in advanced-level judo athletes during *harai-goshi* (4.0 ± 0.6 times body weight) compared to beginners (3.3 ± 0.2 times body weight). Additionally, advanced athletes reached the peak force in less time in the two executed techniques (*harai-goshi* = 117 ± 33 ms; *uchi-mata* = 127 ± 20 ms) compared to beginners (*harai-goshi* = 178 ± 29 ms, *uchi-mata* = 197 ± 27 ms).

In addition to the aspects traditionally considered for the elaboration of strength training, it is necessary to consider, for combat sports athletes, some important additional aspects: (1) the determinant scoring actions during the matches involve recruiting different body segments in a different way, i.e., it is very common for the upper and lower limbs to perform asymmetrical actions, something that is uncommon in classical exercises used during strength training sessions; (2) many throwing and kicking techniques involve high power application with reduced support base, i.e., the completion of execution is done with only one foot - and often only the forefoot-in contact with the ground [1]. Thus, exercises that contemplate these characteristics must be incorporated into the training process.

4. Monitoring and control of the evolution of muscle power in combat sports athletes

As sport professionals, the first goal is to carry out the training planning and, in the sequence, to execute it aiming at the improvement of the athletic performance, mainly in competitions. The first goal seems to be a less complicated task. Efficient planning can be done if the principles of specificity, overload and progression are followed [1,65]. But unfortunately, it is not part of the planning of many coaches to monitor the most important physical capacities for competitive success in certain sports. Without a proper monitoring of the athlete throughout the season, it is very difficult to know if the athlete is responding to the training program in an expected way. Often this important step is neglected by lack of interest on the part of coaches or by lack of criteria for choosing and applying the tests. Therefore, in this section some criteria that should be considered for the choice of a test will be presented, later the tests used to measure muscle power in the grappling and striking combat sports will be presented, and finally, suggestions regarding the moment of throughout the competitive season of the athlete will be made.

4.1. Criteria for Test Choice

According to Kiss and Böhme [66], the following criteria must be considered when choosing a test, regardless of age, sex and sport:

- Definition of the objectives of the program: the initial phase, after defining the objectives of the program, it will be possible to choose the tests best suited to the needs and objectives proposed.
- Origin and year of publication of the test: in some cases, it may be that the test has undergone adaptations or that a new test, more appropriate to our needs, has been created.
- Test objective: does it offer the measure for the intended physical capacity?
- Age and gender to which the test is intended: Is it appropriate to apply this test to my athletes? Is there any way of comparison and classification?
- The scientific authenticity of the test: is the test valid and reliable?

- Standardization of the test: is the test well described and standardized?
- By what means the results obtained can be interpreted and evaluated: how will the result be used? Is there a standard or will a comparison be made with the results of my athlete or group of athletes?
- The possibility of application: Do I have the material to apply the test? Is the space adequate? Are the evaluators prepared, do they know the procedures for applying the test? Is there time available?
- The degree of test difficulty: can my athlete understand the procedures and objectives of the test?
- Results offered: are the results accurate? How will the results be used to prescribe the training?

4.2. Tests used to measure muscle power in grappling and striking combat sports

Usually, four methods are used to calculate muscle power [67,68]: (1) The first method describes the displacement data; (2) The second involves the ground reaction force, given by a force platform; (3) The third method involves a combination of ground reaction force and displacement data; (4) The fourth method involves the use of an accelerometer.

The linear position transducer consists of a compact box, which contains a flexible steel cable wound in a coil, the end of which comes out through a hole in the box [69]. The end of the cable is attached to the bar so that it can only be monitored in the upright position. A spring on the coil keeps the cable under enough strain to return when there is no external pulling force. The linear position transducer and its use can be seen in Figure 9, 10 (A-F) and 11 (A-D).

Figure 9: Linear position transducer.

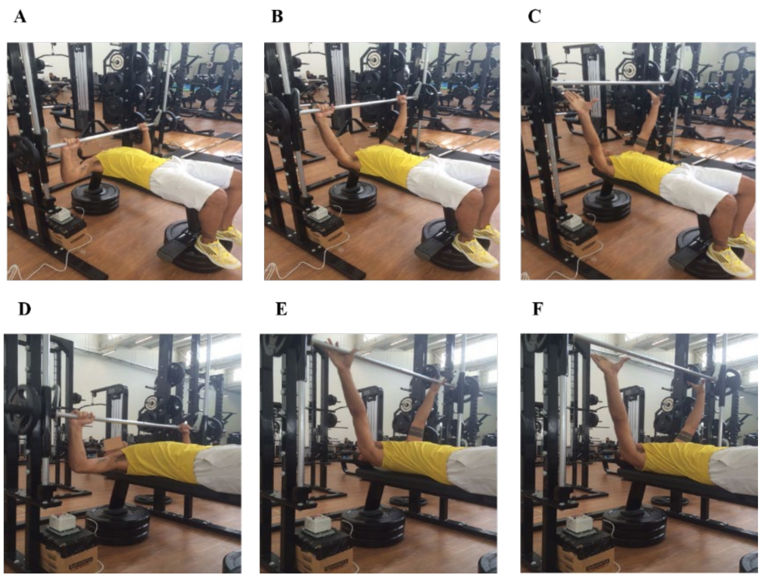


Figure 10: Exercise of the bench press exercise with a linear position transducer attached to the bar.

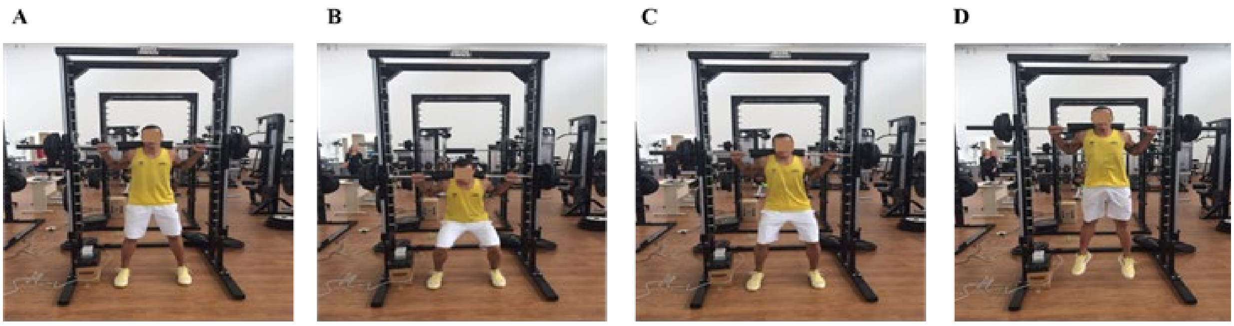


Figure 11: Execution of the loaded squat jump exercise with linear position transducer attached to the bar.

The force platform can capture the impact exerted on its surface, called the ground reaction force. Generally, the force platform is used in the horizontal position, however, it has recently been positioned in vertical so that it can be used by combat sports athletes during the application of a punch [59]. The use of the force platform in the horizontal and vertical position can be observed in Figure 12 (A-C) and 13 (A and B).

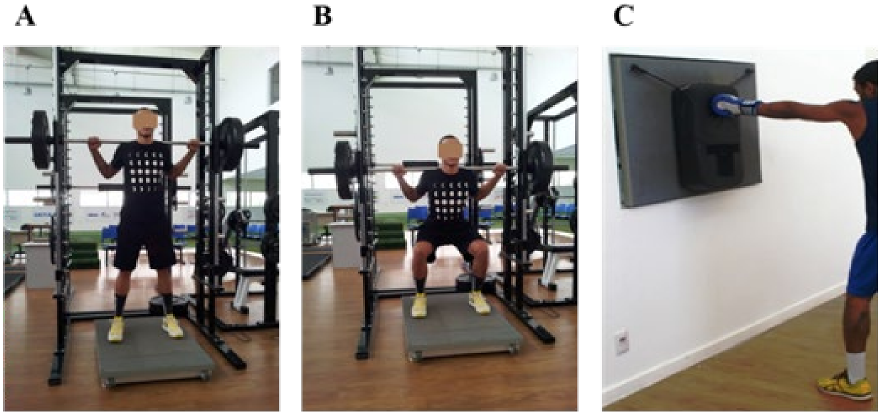


Figure 12: Force platform in the horizontal (A and B) and vertical (C) positions.

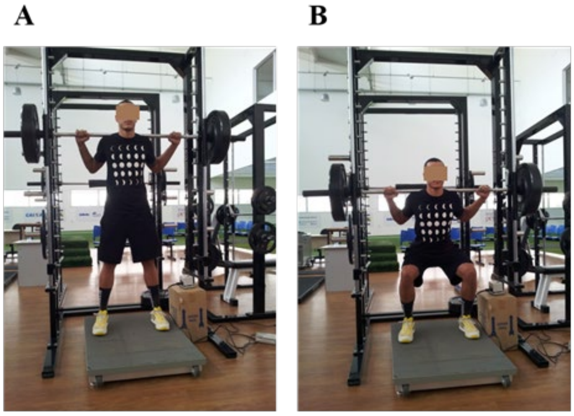


Figure 13: Strength platform and linear position transducer being used while performing the squat exercise.

The fourth method is to use an accelerometer. The accelerometer produces a voltage equal to the acceleration it suffers [69]. Modern equipment is small and light. However, it is noteworthy that the methods described above have some limitations, such as the inability to measure the muscle power of complex actions. These methods can be used mainly during linear movements.

Another way to measure the muscle power in athletes and practitioners of combat sports is through tests involving some variations of the vertical, horizontal and drop jumps, which are widely used among athletes involved with striking combat sports such as boxing [30], karate [70,71] and taekwondo [72]. These tests are also used among grappling combat sports such as judo [73] and jiu-jitsu [52]. In Figure 14 (A – C) and 15 (A – D), the vertical jump and the jump on the contact mat can be observed.

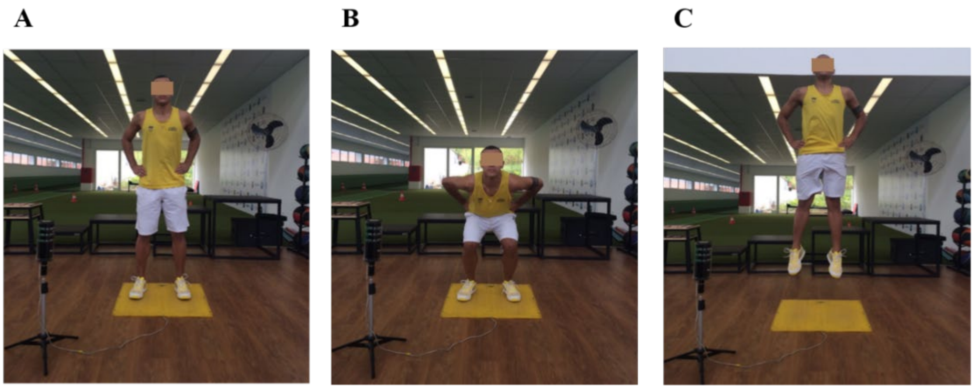


Figure 14: Execution of the vertical jump with countermovement (A-C).

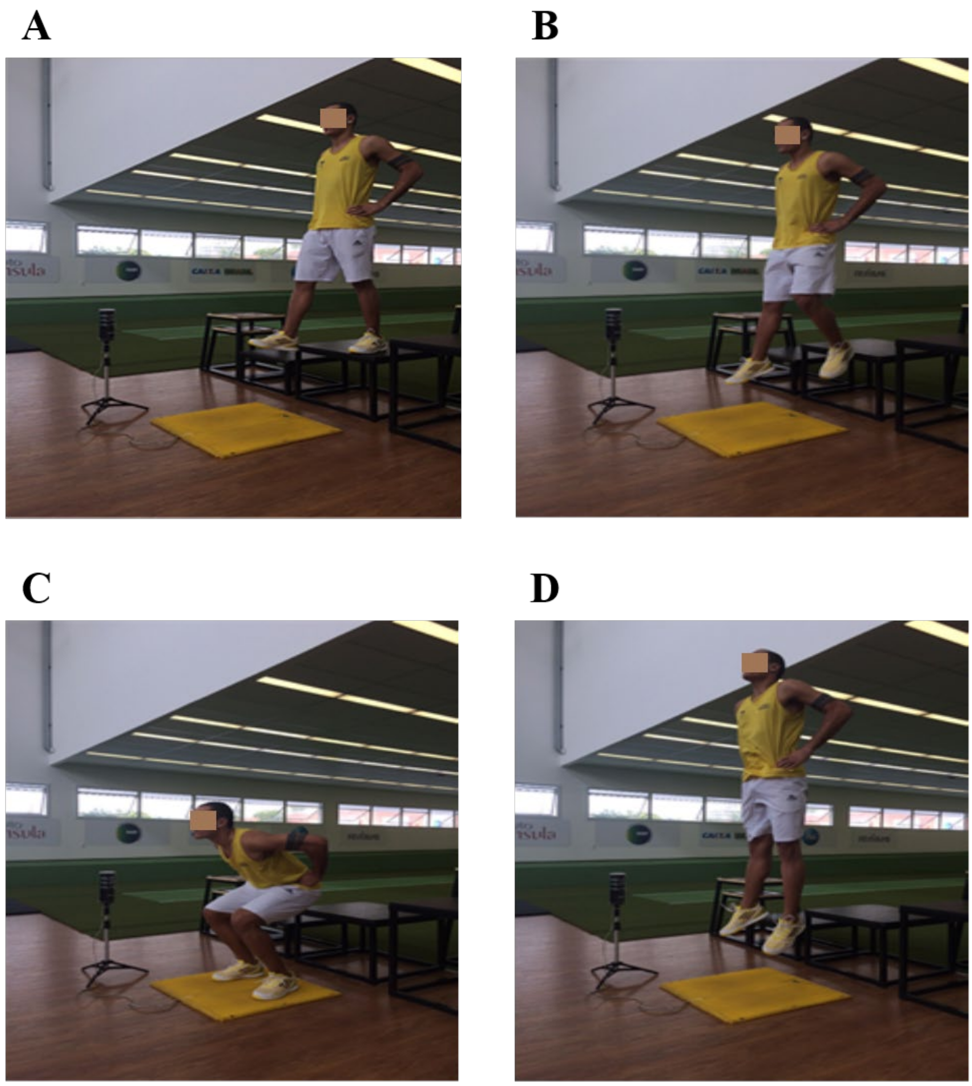


Figure 15: Performing the drop jump to determine the optimal height (A-C).

4.3. Striking and grappling combat sports measurements

In striking combat sports, muscle power is measured during tests in which the athlete performs a single blow, and the punch is the main technique used, measured by a force platform and the accelerometer. These tests have differentiated athletes according to the competitive level (elite, intermediate and beginner) [58] and performance during a match (winners and losers) [74].

Smith et al. [58] measured performance during two punches, jab and straight, by boxers of different competitive levels (elite, intermediate and novice). As expected, the elite group athletes performed better than the intermediate group athletes, who in turn presented superior performance to the novice athletes (Jab – elite: 2847 ± 225 N; intermediate: 2283 ± 126 N; novice: 1604 ± 97 N; straight – elite: 4800 ± 227 N; intermediate: 3722 ± 133 N; novice: 2381 ± 116 N). The performance during the direct punch was higher than the jab for all groups tested.

Loturco et al. [75] analyzed the relationship between impact during fixed distance jab, self-selected distance jab, fixed distance cross and self-selected cross punches with the muscle power and maximal isometric force and found positive relationships varying from 0.67 to 0.85. Muscle power and maximal isometric force variables included the CMJ height, mean propulsive power during jump squat and bench throw, maximum isometric force and rate of force development during squat and bench press. Therefore, muscle power and maximal isometric force are variables that when improved are likely to positive affect punch impact, which is a key element in boxing performance. Thus, these variables can be used during training monitoring and during strength and conditioning training sessions.

Dunn et al. [76] reported positive relationships between boxing punch force, punch impulse and punch force at 5ms and lower-body strength characteristics, but not with lower-body rate of force development or upper-body strength and power variables in male amateur boxers. Specifically, peak punch force for was positively correlated with CMJ force (r = 0.683) and isometric midthigh pull force (r = 0.680), suggesting that maximal strength development is related to punching performance. Moreover, they found significant differences between boxers with the highest and lowest punch forces for isometric midthigh pull force and rate of force development percentage, CMJ force and power, with higher values for those boxers who had the highest punch forces.

Another test used to evaluate boxers is the frequency speed of punch (FSP) [77]. The FSP consists of three steps. In the first one the speed of a single blow, the jab, is measured. In the second step, punches are executed during 5s. Finally, in the third step, the athlete hits for 15s. The FSP presented good reproducibility for the three steps (r = 0.84 and 0.95). However, the FSP did not differentiate athletes by their competitive level during the application of a single punch, but when the application of punches during 5s and 15s were executed there was a statistical difference between competitive levels (amateurs vs athletes - 5s: 25 rep vs 31 rep; 15s: 79 rep vs 89 rep). This difference may not have existed in the first study because there were no elite athletes among the groups [77].

To investigate the acceleration during a punch (*giaku-tsuki*), international level karate athletes were studied [71]. The athletes performed the punch in four different conditions: 1) fixed distance, aiming to generate the highest velocity; 2) fixed distance, aiming to generate the greatest impact; 3) self-selected distance, aiming to generate the highest speed; and 4) self-selected distance, aiming to generate the greatest impact. Male athletes performed better than female athletes. There was a statistical difference in the acceleration of the punch, with the superiority of condition 4 over condition 1, for athletes of both sexes.

Other tests performed with non-specific gestures are used to measure muscle power among karate athletes [71,74]. The squat and the propulsive bench press, using the load related to the athlete's body mass [71] and also percentages of 1RM [74]. Loturco et al. [71] analyzed whether there was a correlation between body mass and the acceleration of the *giaku-tsuki* punch technique between bench press and squat exercises performed with propulsion between winner and loser athletes [74]. In this condition, it was reported a higher muscle power by the winning athletes during the exercise of the bench press exercise and squat in comparison to the defeated athletes (peak muscle power – 30% bench press: 253 W ± 9 W vs. 206 W ± 6 W; 30% squat: 299 W ± 6 W vs. 270 W ± 23 W). Roschel et al. [74] investigated whether the intensity of the exercise could differentiate the level of the athletes. The authors reported that the exercise performed with a more intense load (60% 1RM) did not differentiate the winning and defeated athletes in terms of muscle power generation in squat and bench press exercises [74]. This test performed with lighter loads (30% of 1RM) seems to differentiate high-performance karate athletes (winners and losers).

For grappling combat sports, the optimal load has been determined for the bench press throw [21] and for the prone bench pull [22]. Silva et al. [21] determined the bench press throw peak power for advanced and non-advanced BJJ athletes and reported that groups did not differ concerning power achieved with 30% (advanced: 972 ± 166 W; non-advanced: 890 ± 146 W), 40% (advanced: 1015 ± 197 W; non-advanced: 931 ± 156 W), 50% (advanced: 1032 ± 173 W; non-advanced: 906 ± 126 W), and 60% of 1RM (advanced: 901 ± 176 W; non-advanced: 885 ± 135 W). When both groups were considered together the values achieved with 60% of 1RM were lower than those achieved with 40% and 50% of 1RM, but did not differ from those with 30% of 1RM. Additionally, for the advanced group, the values achieved with 60% of 1RM were lower than those with 40% and 50% of 1RM, but these differences were not found for the non-advanced group. Moreover, when groups were considered isolated or whole, the optimal load was approximately 42% of 1RM.

Tavares et al. [22] compared these same percentages of 1RM, but using the prone bench pull exercise and indicated that mean power mean velocity, mean propulsive power and mean propulsive velocity were lower during 30% and 60% of 1RM compared with 50% and 60% of 1RM, whereas mean propulsive power with 50% of 1RM resulted in higher values than 40% of 1RM (Table 1). The polynomial adjustment indicated that the optimal load for all power and velocity-related variables was 45%.

Table 1: Percentage of one-repetition maximum (1RM), absolute load, mean power (MP), mean velocity (MV), mean propulsive power (MPP) and mean propulsive velocity (MPV) during the prone bench pull executed by Brazilian jiu-jitsu athletes (adapted from Tavares et al. [22]).

Intensity	Load (kg)	MP (W)	MV (m/s)	MPP (W)	MPV (m/s)
30% 1RM	26.6 ± 7.9	950.2 ± 177.2[a]	0.95 ± 0.05[a]	1037.7 ± 130.3[a]	0.97 ± 0.04[a]
40% 1RM	35.7 ± 10.6	2289.5 ± 163.8	1.11 ± 0.07	1350.6 ± 123.2	1.21 ± 0.07
50% 1RM	44.6 ± 13.2	1135.5 ± 151.93	1.12 ± 0.06	1472.1 ± 133.9[b]	1.27 ± 0.06
60% 1RM	53.6 ± 15.9	930.7 ± 88.5[a]	0.88 ± 0.08[a]	1110.2 ± 80.7[a]	0.89 ± 0.08[a]

[a]Lower values than 40% 1RM and 50% 1RM ($p < 0.05$); [b]Greater values than 40% 1RM ($p < 0.05$).

4.4. Application throughout the competitive season

According to Kiss and Böhme [66], the evaluation of sports training should be performed before, during and after the sports training phases, with the following purposes:

a) At the beginning of the season: it has the function of diagnosing the condition of the athlete and the elaboration of goals to be achieved. This evaluation is called diagnostic.

b) During the season: it has the function of monitoring the training process and reaching the proposed objectives. If necessary, the objectives should be reformulated. This assessment is called formative.

c) At the end of the season or a specific phase: it has the function of attesting the effectiveness and the achievement of the objectives proposed for the training process. This assessment is called summative.

Performing initial performance tests after conducting a needs analysis to achieve high performance contribute to the completion of the planning and the tests applied throughout the season provide feedback for the planning and implementation of the training program as expected. The performance evaluations at the beginning, during and throughout the season are usually conducted in several modalities [78–80]. In combat sports it is no different, the performance tests are applied throughout the season to monitor the performance of the athlete [81], being intensified with the proximity of the competitions [82,83].

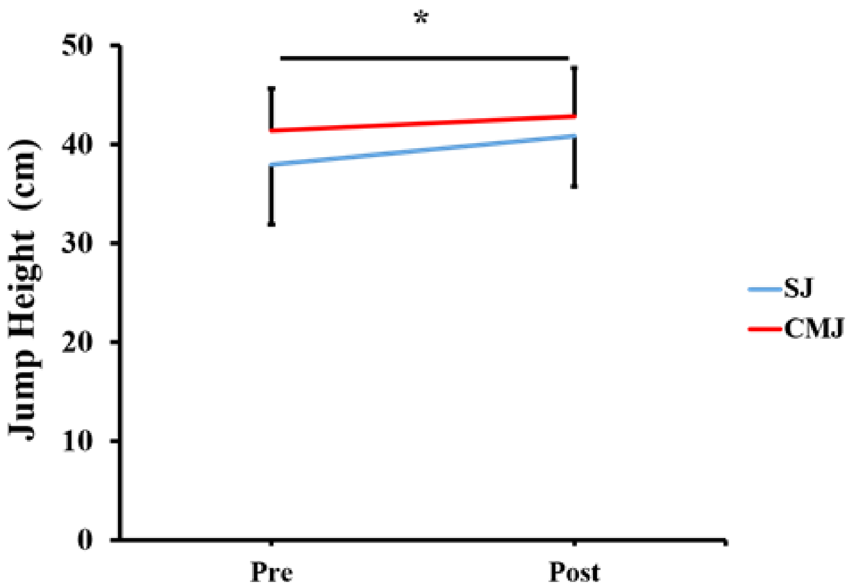
Taekwondo athletes had their muscle power tested weekly for a period of nine weeks prior to boarding for the 2008 Beijing Olympics [82]. The tests used for this purpose were vertical jump variations. This retrospective study showed that athletes improved muscle power during the pre-competition period. With weekly tests to measure the performance of athletes, there was a monitoring of the training program applied, allowing adjustments to the training routine in case the objectives were not reached. Another important point was the test used, the vertical jump, which was probably chosen for the easy attainment of the measure since it requires only the use of a contact mat and the accomplishment of a task usually known by athletes of different sports modalities.

Paralympic judo athletes had their muscle power assessed along a Paralympic cycle, including ParaPan American Games, World Championship and Paralympic Games [84]. The authors applied the SJ, CMJ, prone bench pull, jump squat and bench press in different moments from June 2013 to August 2016 to monitor the muscle power of these parathletes and identified that the best results were achieved close to the Paralympic Games.

5. Longitudinal studies on the manifestation of muscle power in combat sports athletes

To date, few longitudinal studies have been conducted to investigate the effect of training on combat sports athletes' muscle power manifestation. However, it seems that sports professionals should be aware of the variation of the training (periodization) and the choice and specificity of the exercises, only in this way the training can cause positive effects to the performance of the athletes [85]. Additionally, it seems that traditional strength training does not cause positive changes in the performance of the gesture performed during the match of athletes involved in the practice of striking combat sports [86]. In order to cause the desired adaptations, more specialized training is required in highly specialized athletes [4,5].

In the Ke-tien study [85], the objective was to describe the effect of 20 weeks of strength training and muscle power on taekwondo athletes' performance. The muscle strength and power training was divided into five phases, with the following objectives: 1) weeks 1-6: general physical conditioning (4 exercises, 25-40 repetitions, intensity between 25-45% of 1RM); 2) weeks 7-12: muscle hypertrophy (8 exercises, ~ 10 repetitions, intensity between 75-85% of 1RM); 3) weeks 13-16: maximum strength (7 exercises, 3-5 repetitions , intensity between 40% of 1RM to hang snatch, 45% of 1RM to power clean and hang clean and 95% of 1RM to another exercises); and 4) weeks 17-20: muscle power (6 exercises, 3-5 repetitions, intensity between 80-90% of 1RM). The training was conducted three times a week. The athletes performed the SJ and the jump with CMJ before and after 20 weeks of training. Athletes increased jump height after the training period, as can be seen in Figure 16. Athletes improved 7.1% and 3.3% in SJ and CMJ, respectively.



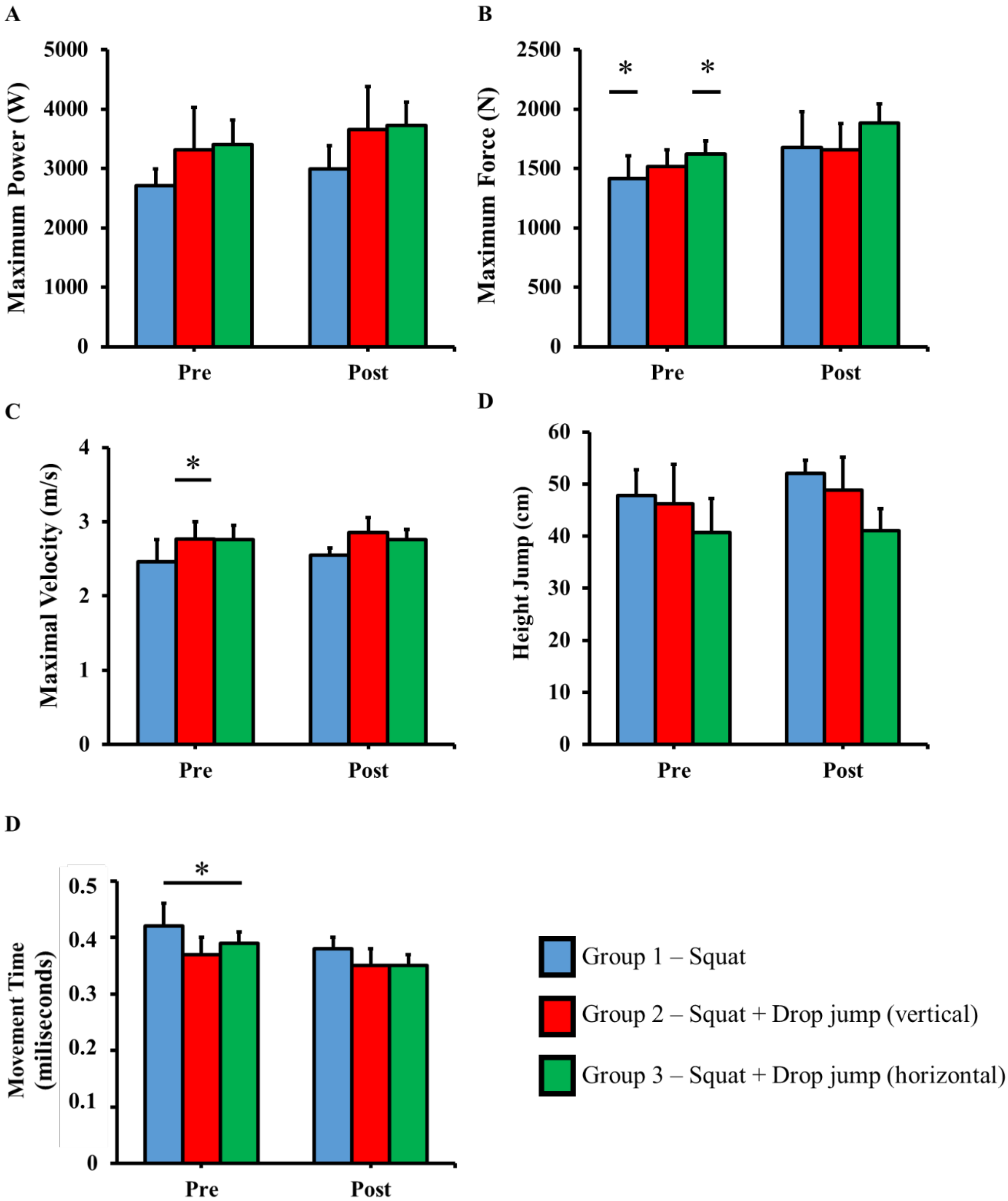
Note: * statistically significant difference (p <0.05) between the pre- and post-intervention moments in both tests.

Figure 16: Performance in muscle power test after 20 weeks of training (Adapted from Ke-tien [85]).

The study by Tsai et al. [87] aimed to compare the effect of three different training structures, performed over a period of 8 weeks, using taekwondo athletes. The groups trained as follows: 1) training using half squat exercise; 2) combination of vertical jump and half squat exercise, and 3) combination of horizontal jumping and half squat exercise. The volume and intensity used are shown in Table 2. Athletes who performed traditional strength training, using only the squat exercise, improved maximum strength (Figure 17 B). On the other hand, athletes who performed the training using variations of plyometric exercises improved the maximum power, maximum strength, speed and time of a blow (Figure 17 A, B, C, and E).

Table 2: Training protocol used by taekwondo athletes (Tsai et al. [87]).

Strength training (squat)			
Weeks	Intensity (%)	Repetitions	Rest interval (min)
1st -2nd	80	5	2
3rd -4th	85	4	2
5th -6th	90	3	2
7th -8th	95	2	2
Power training (drop jump)			
Weeks	Intensity (cm)	Repetitions	Rest interval (min)
1st -2nd	50	10	3
3rd -4th	57	10	3
5th -6th	64	10	3
7th -8th	71	10	3



Note: * difference between pre- and post-at the same points (p <0.05).

Figure 17: Pre and post-training performance of taekwondo athletes (Adapted from Tsai et al. [87]).

The study by Voigt and Klaussen [88] investigated the effect of three strength training routines on the muscle power of the punch performed by karate athletes. The duration of the training was 20 weeks. The karate's group 1 (G1) underwent strength training for 16 weeks with heavy loads combined with training with light loads in the punching bag, followed by four weeks of intensive training in the punching bag. The karate's group 2 (G2) underwent training in the punching bag combined with punch exercises and intensification of training between the eighth and the sixteenth weeks. Group 3 (G3) was formed by non-karate athletes who performed sixteen weeks of strength training, followed by seven weeks without strength training. The results were as follows: all groups presented performance improvement for dynamic force, between 14% and 53%. G1 showed an increase in hand (10.1%) and shoulder speed (34.7%) during the first sixteen weeks of strength training. G2 presented an increase in the angular velocity of the shoulder until the sixteenth week (34.7%). G3 did not show any increase in angular velocity of the hand and shoulder but showed an improvement in the angular velocity of the elbow during the initial sixteen weeks (12.8%). Between the sixteenth and twentieth weeks, the G1 reduced the maximum shoulder velocity, without significant change in muscle strength. During this period the karate athletes discontinued strength training with high loads and kept only the training in the punching bag. Strength training with high loads carried out isolated did not influence the speed of specific movement of karate athletes. On the other hand, specific punch training was effective in increasing punch velocity and better utilizing the stretching-shortening cycle of the shoulder flexor and elbow extensors muscles. Finally, the results indicated that strength training is able to improve movement speed only when combined with specific punch training.

In the study by Seo et al. [89] the effect of 8 weeks of physical training on the performance of taekwondo athletes was investigated. Athletes performed strength, muscle power, and metabolic training during the 8 weeks. When the results of the pre- and post-tests were compared, there was a variation of 0.2% for male athletes and 2.2% for female athletes (values in delta percentage). However, there was no statistical difference between the pre- and post-training moments. The mean value of the horizontal jump is shown in Figure 18. Probably, the result achieved in this study should be associated with the lack of specificity of the training performed.

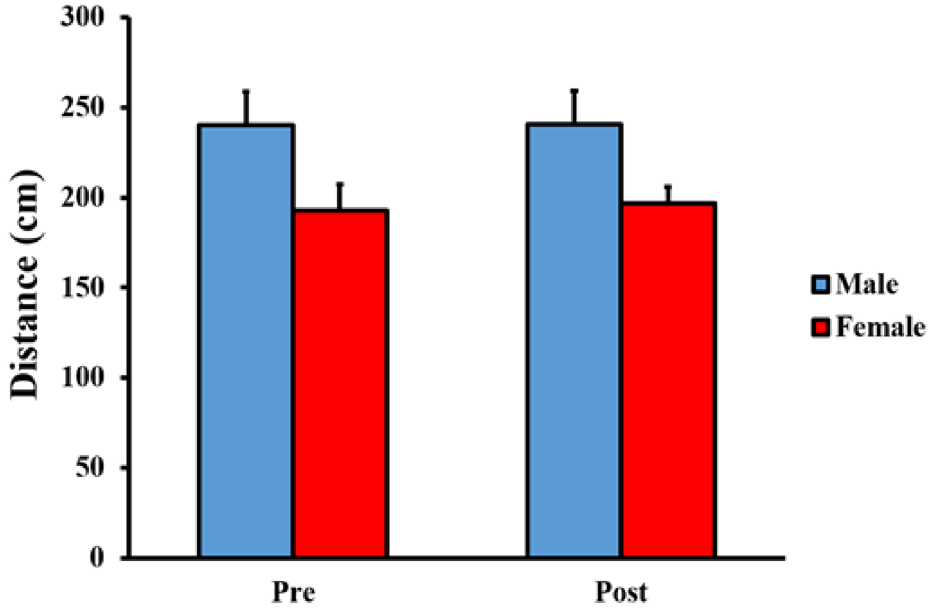


Figure 18: Performance in the horizontal jump pre- and post-20 weeks of training (Adapted from Seo et al. [89]).

Training programs for strength and muscle power using conventional gestures alter the performance of untrained or non-athletes [90]. However, more specific power training is needed to improve the performance of elite athletes [90]. Among taekwondo athletes, Jakubiak and Saunders [28] had the objective of investigating the effect of a specific training technique (*Bandal-Tchagui*), against the resistance of an elastic band, on the development of muscle power. Twelve taekwondo athletes were divided into two groups with six athletes in each group. The athletes performed the training three times per week for four weeks. The taekwondo training sessions were not interrupted. The training was composed by three sets of six repetitions with 1-min rest interval between sets. The number of sets and the strength provided by elastic increased progressively. Each week an exercise set was added, and the elastic tube was lengthened by 30 cm. This elongation of the elastic tube linearly increases the resistance against movement. There was a statistical difference in the experimental group. The athletes who performed the training improved the semicircular kick speed (*Bandal-Tchagui*) after the training period in comparison to the movement performed before the training period, whereas the athletes in the control group had a non-significant variation of 0.1%. The velocity of the *bandal tchagui* was improved in five of the six athletes in the experimental group (between 5% and 17%), but increased in only one athlete in the control group (6%). One-point worth emphasizing is that the resistance imposed by the elastic band cannot be so high as to be detrimental to the movement pattern of the technique that will be performed. Thus, an additional overload, caused by the elastic band, will only be beneficial if the technique pattern is not changed.

The study by Olsen and Hopkins [29] aimed to investigate the effects of training conducted with ballistic action attempts on kicking performance. The dependent variables used were: frontal kick, lateral kick and a blow with the palm of the hand. The study participants were divided into two groups, the experimental group (n = 13) and the control group (n = 9). The experimental group underwent strength training during the first 8 weeks, three times per week, two sets in the first week and three sets between the second and eighth weeks. Subsequently, the athletes of the experimental group performed strength training and ballistic training between the tenth and ninth weeks. Conventional strength training was performed twice per week. Ballistic training was performed three times per week, with a volume of four sets of ten repetitions during weeks ten and eleven, increasing to five sets of ten repetitions between weeks twelve and nine, in addition to practicing combat sports-specific training. The control group underwent combat sports-specific training during the first nine weeks, followed by additional front kick training three times a week. During weeks 10 and 11, four sets of ten repetitions per leg were performed. During the weeks twelve to nineteen, five sets of ten repetitions per leg were performed. The experimental group, which performed the conventional strength training, obtained a 12% improvement in the force generated during the frontal kick, in comparison to the control group. Ballistic training and conventional force training reduced lateral kick strength by 15% but increased movement speed by 11-21%. Ballistic training was more efficient at improving the performance of more experienced athletes. Thus, attempting to perform ballistic movements during training may be the best strategy for skilled athletes in combat sports where the strength and speed of movement execution are critical variables for performance.

Franchini et al. [91] aimed to determine the most efficient strength training method for judo athletes. Thirteen athletes participated in the study and were divided into two groups. Three strength training sessions were conducted for eight weeks, as shown in Table 3. Athletes performed a test battery before and after the training period. The measure of muscle power used was the horizontal jump. The first group, composed of six athletes performed the linear periodization, the second group, composed of seven athletes performed the non-linear undulating periodization. After the training period, there was no statistical difference between the groups nor between the pre- and post-moments for muscle power (Figure 19).

Table 3: Periodization of strength training used in the study by Franchini et al. [91].

	Linear			**Non-Linear (undulating)**		
	1st week	2nd week		1st week	2nd week	
Monday	3-5 RM	3-5 RM		3-5 RM	Power Exercises	
Wednesday	3-5 RM	3-5 RM		Power Exercises	15-20 RM	
Friday	3-5 RM	3-5 RM		15-20 RM	3-5 RM	
	3rd week	4th week	5th week	3rd week	4th week	5th week
Monday	Power Exercises	Power Exercises	Power Exercises	3-5 RM	15-20 RM	Power Exercises
Wednesday	Power Exercises	Power Exercises	Power Exercises	Power Exercises	3-5 RM	15-20 RM
Friday	Power Exercises	Power Exercises	Power Exercises	15-20 RM	Power Exercises	Power Exercises
	6th week	7th week	8th week	6th week	7th week	8th week
Monday	15-20 RM	15-20 RM	15-20 RM	Power Exercises	15-20 RM	15-20 RM
Wednesday	15-20 RM	15-20 RM	15-20 RM	15-20 RM	Power Exercises	3-5 RM
Friday	15-20 RM	15-20 RM	15-20 RM	3-5 RM	15-20 RM	Power Exercises

Note: RM: Repetition Maximum

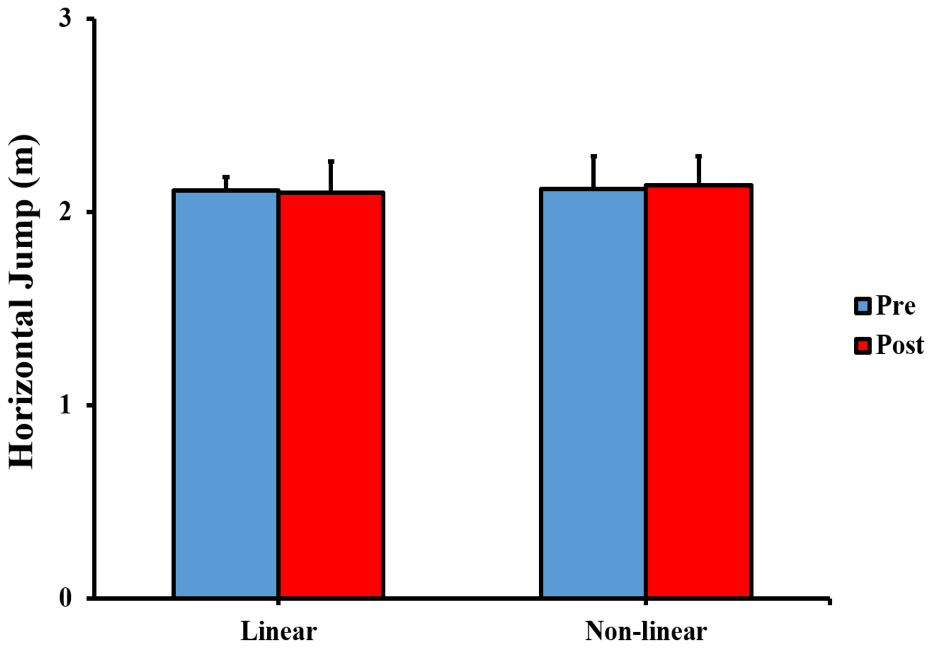


Figure 19: Performance in the horizontal jump before and after eight weeks of strength training with different load distributions (Adapted from Franchini et al. [91]).

Marques et al. [92] applied block periodization concepts to national and international level judo athletes and compared their responses to such training process, with five weeks of accumulation phase, five weeks of transmutation phase and three weeks of realization phase. During the accumulation phase, athletes executed strength exercises and conditioning workouts to develop judo-specific strength (i.e., muscle power in lower- and upper-body and strength-endurance in upper-body - especially the forearm muscles - and core regions). For the transmutation phase, training was directed to develop muscle power, including weight training, plyometrics and judo-specific actions. During the realization phase, the training was similar to the transmutation phase, but the volume was reduced and judo technical actions were the main focus of the training phase. The authors tested the athletes concerning muscle power (CMJ and SJ), judo-specific test (SJFT) and maximal strength (row exercise 1RM). For the muscle power variables assessed there were no effects of competitive level, training phase or interaction. Although lower-body muscle power is relevant for judo performance, the fact that both CMJ and SJ are shorter than the duration of a judo throwing technique (approximately 1.14s) and are executed with no load, are aspects that have been used to suggest that the typical judo training adaptation could not be detected by these tests [93].

Kostikiadis et al. [94] compared the effects of a 4-week low-volume strength and conditioning training program based on circuit training with a regular conditioning training program. Strength and conditioning training were performed three times per week every 2 days (Monday, Wednesday, Friday), whereas in the intermediate three days (Tuesday, Thursday, Saturday), all athletes followed the same MMA training, focused on technical skills, striking and grappling. The strength training group executed strength and power exercises (i.e., squat, bench press and deadlift at 80-95% of 1RM followed by 3 CMJ jumps, 2-kg medicine ball throws, and jump shrugs with 45% of the deadlift load after each set, respectively, with 1 min rest between the three repetitions of each power exercise), and 10 min after they performed a rowing aerobic high-intensity interval training (details not provided here due to the goals of the present chapter) in the first and third sessions of the week. The second session in each week was directed to improve muscle power and speed (i.e., loaded jump squats in a Smith machine, with 4-min intervals, during which they performed drop jumps using individual optimal drop height, with 12s intervals; 4 sets of 8 reps of a 4-kg medicine jab punch throws. After 1.5 min of rest between sets, they performed 8 plyometric push-ups, with 12s between repetitions; then, the athletes performed 5 x 10m weighted sled maximum sprints with 4-min intervals, using loads to allow for a fatigue index lower than 10%, and 5 x 10 m unloaded sprints with 4-min intervals; then, a sprint interval training, involving 6 x 40 m shuttle sprints with change of direction each 10 m and 20s intervals between sets). The other group followed their regular strength and conditioning training routine plus the following training sessions: First and third sessions –

circuit workout using squat, military press and kettlebell swings, followed by 20 min of rope skipping at 70-80% predicted maximum heart rate; Second session – circuit training (5 rounds) using kettlebell swings, clean and press, sumo deadlifts high pull, executing the maximum number of repetitions in 1 min with 1 min between exercises. Then, they executed 20 min of rope skipping. After the 4-week training significant improvements were found for the strength training group but not for the regular strength training group. Concerning muscle power, the strength training group improve the SJ power (pre: 1195 ± 122.5 W; post: 1230 ± 6 W), right (pre: 10.5 ± 0.9 m/s; post: 11.6 ± 0.8 m/s) and left arm medicine ball throw velocity (pre: 9.8 ± 0.6 m/s; post: 10.3 ± 0.9 m/s), 10 m sprint time (pre: 1.95 ± 0.06 s; post: 1.88 ± 0.05 s), and 2-m 75 kg dummy take down (pre: 0.96 ± 0.1 s; post: 0.74 ± 0.01 s). Moreover, these post-training values were better than those presented by the regular training group. Therefore, low-volume high-intensity training was more appropriate to improve muscle power performance of MMA athletes.

6. Means and methods for the development of muscle power in combat sports athletes

A training session aimed at the muscle power development can be described by the acute variables of the program, as follow description.

6.1. Exercise choice

The choice of exercises that will compose the training sessions involves many decisions, from the equipment to be used to the type of muscle action [95]. The number of joint angles and possible exercises to be performed are almost infinite. Additionally, we know that when a muscle is not activated, it will not undergo any type of adaptation and, consequently, will not contribute to a better performance. For this reason, the choice of exercises should be a careful analysis of the athlete's needs in face of the requirements of the modality practiced [95].

In combat sports, complex movements are often performed, which includes jumps and twists [27,60,96,97]. In the application of some techniques, usually, each member is performing a different action, sometimes in different directions. For this reason, the exercises to be used in the training session should stress the muscles that are activated during the match, preferably at specific joint angles and muscle actions. Thus, to choose the exercises, an analysis is necessary, initially responding to some questions that affect the elaboration of the program. These questions are [98]:

1. What are the metabolic demands?
2. What are the biomechanical demands?
3. What are the main injury sites for a specific combat sport and the athlete's injuries history?

Among the main exercises used for the development of muscle power are the traditional, ballistic, plyometric and Olympic weightlifting style and its variations [4], as exemplified in Table 4.

Table 4: The main exercises used for muscle power training routines.

Exercises for muscle power development	Weightlifting derivatives	Ballistic exercises
Snatch	Power snatch	Bench Press
Clean and Jerk	Power clean	Pull
	Clean	Squat
	Snatch pull	
	Hang clean	
	Jerk	

6.2. Traditional resistance training exercises

The most commonly used strength exercises in a training program are the back squat and bench press. These exercises are relevant in the early stages of the training program or for athletes who have low levels of strength [4]. However, it has been suggested that as soon as muscle strength and power levels increase, the effectiveness of this exercise decreases [4].

During training with traditional strength exercises, there is a deceleration in the final phase of the movement [99,100]. For example, during bench press exercise, the duration of the deceleration phase represented 14% of the total time with 104% of 1RM, 23% with 100% of 1RM and 52% with 80% of 1RM [99]. When the bench press exercise was performed in an explosive manner with 45% of 1RM, the deceleration phase lasted 40% of the total movement [100]. This fact is contrary to what happens during the application of a combat sport technique, when the movement is accelerated at the final phase, and often the athlete projects to complete the execution of the technique. The deceleration phase of the movement is explained by the reduction of the activation of the agonist musculature and the increase of the activation of the antagonist muscles [100]. As a result of the deceleration of movement in the final phase and the lack of specificity with the gestures of the combat sports, the transfer can be impaired [4].

Although the traditional exercises for strength and power training are important, it will be necessary to perform other, more specific, mechanic stimuli so that muscle power continues to be developed [4].

6.3. Ballistic exercises

The problem of the deceleration phase is solved with the use of ballistic exercises. Many times, the ballistic exercises predict the projection of the implement or the body weight itself at the final phase of the movement, eliminating the deceleration. The main exercises used are squats and bench press. The intensity in which ballistic exercises are performed varies between 0-80% of 1RM obtained during exercises performed in a traditional way [4].

Previous studies have compared kinetics, kinematics, and neural activation of the bench press exercise performed in a traditional and ballistic manner [100]. Superior performance has been observed during ballistic exercise when compared to the same exercise performed in a traditional manner. In addition, mean muscle activation during the concentric phase for the pectoralis major, anterior deltoid, triceps brachii, and biceps brachii muscles were higher (19%, 34%, 44%, and 27% respectively) during the ballistic exercise in comparison to the traditional execution [100]. In addition, it was observed that eight-week jump squat exercises involving well-trained athletes (volleyball) resulted in improvement in vertical jump compared to the group that performed the training using the squat and leg press exercises during the same period [101]. Thus, it seems that the use of ballistic exercises helps the athlete in the muscle power production during the accomplishment of a specific gesture when compared to the traditional exercises.

6.4. Plyometric exercises

Plyometric exercises are characterized by rapid stretch-shorten cycle (SSC) muscle actions and used by athletes who need to perform explosive movements during the training routine [4]. The most used exercises during a plyometric training session are the deep jumps and some variations of jumps with horizontal and vertical component [102,103]. In addition, multiple jumps, single leg, and box exercises are performed to increase the overload imposed on the muscle and, consequently, the muscle power generated. The basic concept behind plyometric training is to absorb energy during the eccentric phase of movement and move to the concentric phase as quickly as possible, avoiding loss of energy as heat [9]. For example, superiority at jump height has been observed during CMJ as compared with SJ, starting from knee flexion at 90º [104]. This difference in performance has been attributed to the characteristic of each jump. While the SJ is purely concentric, in the CMJ an eccentric phase and a rapid transition to the concentric phase are performed. The reactive force index is influenced by the height of the jump and by the individual's training state, with athletes achieving the best performance.

Traditionally, plyometric exercises are performed with little or no external overload [102]. When some overload is used, usually medicine ball, the goal is to potentiate energy absorption during the eccentric phase of the stretching-shortening cycle [4,5,102,103]. Another resource used for the same purpose is to increase the height of the deep jump [4,5]. Table 5 shows different classifications to be used for the prescription of plyometric exercises.

Table 5: Classification of plyometric exercises (Adapted from Bompa [105]).

Exercise Type	Exercise Intensity	Number of sets and repetitions	Number of repetitions per session	Rest interval between sets
High reactivity jumps	Maximal	5-8 x 10-20	120-150	8-10min
Drop Jumps	Very High	5-15 x 5-15	75-100	5-7min
Multiple jumps	Sub-maximal	3-25 x 5-15	50-250	3-5min
Low reactivity jumps	Moderate	10-25 x 10-25	150-250	3-5min
Low impact, jumps in place, throwing implements	Low	10-30 x 10-15	50-300	2-3min

6.5. Olympic weightlifting exercises and its derivatives

Weightlifting exercises are the snatch and clean and jerk [106]. These exercises are used in training programs for athletes of various modalities [18,79,107]. Olympic weightlifting exercises and their derivatives are proposed as efficient for the development of muscle power [108]. These exercises are chosen by the great power generated during their execution [11,106]. This characteristic is a result of the acceleration generated during the entire propulsive phase of the movement [109,110]. Musculoskeletal changes are also attributed to the use of strength and power exercises, including Olympic weightlifting [4,5,106]. Among these changes are the modification of type IIx fibers to type IIA, increase in maximal strength and muscle hypertrophy, especially type II fibers. Type II fibers have a great capacity to generate muscle power and strength, superior to type I fibers [111–114]. The athletes involved in modalities in which the main characteristic is power, on average, 53% to 65% of type II fibers in the vastus lateralis muscle [115–122]. However, untrained subjects have the same percentage distribution of type II fibers, the difference is that in athletes the cross-sectional area of the muscle is larger [116,117,121,122]. This feature allows athletes to achieve superior performance in power tests and is desired by athletes of various sports, including combat sports. However, it is worth mentioning that there is no study performed with athletes of the combat sports. In fact, few studies have investigated the effectiveness of training for muscle power using Olympic weightlifting exercises.

It is not the purpose of this text to demonstrate the technique of movement of Olympic weightlifting exercises. The technical description of Olympic weightlifting exercises can easily be found in the specialized literature [106,123]. The main objective of this session is to present information that may be useful when planning and selecting the exercises that will be used by the combat sports athletes.

6.6. Complex exercises

Complex training is performed with the aim of stimulating adaptations for muscle strength and power in the same training session [124]. Complex training involves the combination of an exercise performed at high-intensity followed by an exercise performed with low overload, using biomechanically similar movements, in each set [125]. An example of a complex exercise in judo is to perform the squat exercise followed by the *seoi-nage* technique; another example applied to striking combat sports is the execution of bench press exercise followed by a punch technique.

In one of the first literature reviews on the subject, Ebben and Watts [126] made recommendations on the prescription of complex training. Subsequently, several studies have investigated the acute effect of complex training on performance. Among the manipulated variables are mainly the training intensity [16,127] and the interval between conditioning activity (e.g., strength exercise) and the conditioned activity (e.g., main activity) [127–135]. There is evidence that complex training can improve maximal strength and 20-m sprint speed when the complex training is applied for more than 4 weeks [136]. Therefore, complex training can provide positive benefits to key elements of power (i.e., maximal strength and speed), but no chronic study using combat sports athletes was found.

Complex training has been used among athletes practicing striking [16] and grappling combat sports [15]. In the study performed with taekwondo athletes, the complex training was superior to the others in improving the performance during the accomplishment of the task using specific gestures of the modality, the frequency speed of kick test (FSKT) [16]. However, although there was an improvement in performance during FSKT, there was no improvement in performance during CMJ. This result was attributed to the lack of CMJ specificity for the modality. However, another study using a combination of low- (1 x 3 rep) versus high-volume (3 x 3 rep) and low- (50% of 1RM) versus high-intensity (90% of 1RM) strength conditioning activities did not find any improvement in the CMJ or FSKT performance when 10-min rest intervals were used [137].

Aandahl et al. [138] submitted 16 striking combat sport athletes to a 10-min warm-up followed either by 10 kicks using an elastic band (30 N resistance in the initial and 60 N in the final kick phases) or not, and after 5-8 min tested their roundhouse kick performance. Foot kicking velocity increased 3.3% when the elastic band was used, which was explained by the increased muscle activity in the vastus medialis (35.2%) and rectus femoris (43.9%) in this condition. These results that the use of elastic band in combat sport-specific conditioning activity can also improve kick performance.

The study carried out with judo athletes aimed to investigate the effect of different strength and power exercises on performance during a specific judo test [15]. The specific test was the Special Judo Fitness Test (SJFT). This test is divided into three periods: (A) 15 s, (B) 30 s, and (C) 30 s, with 10 s interval between periods. It was observed an increase in performance in the first period after performing 10 sets of three jumps with 30-s intervals between sets and 3-min interval before executing the SJFT (6.4 ± 0.5 throws) compared to the control condition (5.7 ± 0.5 throws). The best test index (13.58 ± 0.72) occurred after performing the complex exercise, being lower than the index obtained after the plyometric exercise (14.51 ± 0.54); lower index represents a better performance in this test. However, it is worth noting that the test index is also influenced by the heart rate after the test, which may have been more determinant for the final test result than the number of throws performed.

Lum [139] compared a regular judo-specific warm-up, a lower-body conditioning activity (3 x 5 standing broad jump) and a lower- and upper-body conditioning activity (2 x 5 standing broad jump plus 2 x 5 elastic band pull simulating the *kuzushi* phase of a judo throwing technique) on the high pull test performance and on the SJFT performance. The interval between these procedures and the high pull test was 5-min long, and between this test and the SJFT a 2-min interval was given. RPE was lower after the two conditioning activities compared with the traditional warm-up. The results indicated that the combined lower- and upper-body conditioning activity improved the high pull test power compared with the traditional warm-up, whereas both conditioning activities resulted in higher number of throws (lower-body: 5.3 ± 0.6 rep; lower- and upper-body: 5.3 ± 0.5 rep) in the set A of SJFT compared with the traditional warm-up (4.9 ± 0.5 rep). This study confirmed that the use of complex training can improve acute judo-specific performance.

Boxers, karate and to a lesser degree taekwondo athlete (because they use few punches, ~ 2% [140]), can benefit from the use of complex exercises for the upper limbs. An example of a complex exercise for the upper limbs is to perform the bench press exercise first, followed by push-ups. Another example is the bench press, followed by specific punching actions.

Some indications for the prescription of complex training aimed at the acute improvement of performance are presented in the literature [55,141]. These studies indicate the most appropriate situation to achieve an acute improvement in performance (Table 6).

Table 6: Characteristics needed for the prescription of complex training aiming at the acute improvement of acute performance (Based on Gouvêa et al. [141], Wilson et al. [55]).

Variable	Better performance
Training status	Athletes
Muscle action performed	Dynamic for lower limbs
Exercise intensity	Moderate (60-84% of 1RM)
Volume	Multiple sets
Rest interval between stimuli	3-10 min

The use of strength and power exercises may benefit the athletes when performing the specific gesture [23,28]. In combat sports, the ability to perform force quickly is often more important than reaching maximum force. In striking combat sports such as boxing, karate, and taekwondo the techniques are applied quickly, as can be seen in Table 7 and, if the athlete is trained to perform powerful movements, he/she may win the combat.

Table 7: Characteristics of different blows according to the combat sport.

Reference	Action	Linear velocity (m/s)	Duration (s)
Karate			
Diacu [142]	Junzuki	5.7 – 9.8	-
	Otoshiuke	10 – 14	-
	Shutouke	10 – 14	-
	Mae-geri	9.9 – 14.4	-
	Yoko-geri	9.9 – 14.4	-
	Mawashi-geri	9.5 – 11.0	-
	Ushiro-geri	10.6 – 12.0	-
Chiu and Shiang [143]	Reverse punch (Gyaku Zuki)	14.7	-
	Straight punch (Oi Zuki)	10.6	-
Gianino [144]	Reverse punch (Gyaku Zuki)	13.0	-
	Straight punch (Oi Zuki)	10.0	-
Daniel and LiviuRazvan [145]	Reverse punch (Gyaku Zuki)	8.2	-
	Kizame Zuki	6.8	-
Cesari and Bertucco [146]	Tate Zuki	Athletes: 7.8	-
		Novices: 6.5	-
Smith 1983	Straight punch (direct)	vmean 11.5	-
Taekwondo			
Pearson [147]	Semicircle Kick	14.6	-
Pieter and Pieter [148]	Semicircle Kick	15.9	-
Serina and Lieu [149]	Semicircle Kick	15.5	-
Conkel et al. (31)	Semicircle Kick	13.4	-
Svoboda et al. [150]	Straight punch (direct)	vmax 8.4	-
		vmean 8.0	-
Boxe			
Walilko et al. [151]	Straight punch (direct)	Vmáx: 13.4	-
		Vmean: 9.1	-
Tong-Iam et al. [152]	Straight punch (direct)	Vmáx: 6.6	-
		Vmean: 6.3	-
House and Cowan [153]	Straight punch (direct)	vmax 8.1	-
		vmean 7.0	-
Cheraghi et al. [154]	Straight punch (direct)	vmax 9.4	-
		vmean 7.8	-
Bingul et al. [155]	Straight punch (direct)	vmean 5.3	-
Kimm and Thiel [156]	Straight punch (direct)	vmean 8.1	-
Atha et al. [157]	Straight punch (direct)	vmax 8.9	-
Kung fu			
Neto et al. [158]	Palm strike	vmax 5.8	-
		vmean 5.5	-
Judo			
Blais, Trilles, Lacouture [159]	Morote-seoı-nage	-	1.14
	Imbalance (Kuzushi)	-	0.56
	Prepation (Tsukuri)	-	0.42
	Execution (Kake)	-	0.16

6.7. Exercise order

Among the variables that are reported in this chapter, the order of exercises is certainly the less studied. For many years the recommendation on the order of the exercises was to perform the exercises intended for the large muscle groups before the exercises for smaller muscle groups [13,160,161]. Another recommendation is that multi-joint exercises should be performed before mono-articular ones [160,161]. This recommendation was made because when a smaller muscle group, considered secondary in some movements, or a mono-articular exercise is performed before, there is a possibility that the training may be less effective for the primary muscle due to the reduced ability to maintain performance during the sets executed at the end of the session [13,162]. However, few studies have investigated these recommendations with the use of protocols involving exercises for muscle power development [162,163].

Another recommendation based on the practical experience of the training relates to the performance of exercises in a priority way, that is, if the training for muscle power is the main objective of the training session, it must be performed first. This design allows the athlete to perform the training aimed at muscle power without fatigue, which could hinder the development of maximum power. On the other hand, in some moments it may be interesting for the combat sports athletes to train power in a situation of fatigue, since many times, several actions are carried out during the same match and several matches in a day of competition [46–49,52].

Another situation in which the exercise should be performed at the beginning of the training session is when it is being improved or even learned [13]. This situation will allow the athlete to perform the movement without limitations caused by muscle fatigue.

Finally, training for muscle power involves performing multi-joint exercises in an explosive manner, which will be best performed if they are performed at the beginning of the training session [4,5]. Inappropriate sequencing of the training session aiming at muscle power may compromise the athlete's performance and shorten the training session [164]. An example of the contents that can be worked on in the same training session is presented in Table 8.

Table 8: Contents to be combined in the same training session (Based on Haff and Haff, [164]).

Primary purpose	Secondary purpose
Muscle Power	Endurance
Muscle Power	Velocity
Muscle Power	Agility
Muscle Power	Maximal strength
Technical training	Muscle power

Usually, the exercises used to train athletes' muscle power are multi-articular because they resemble what happens during sports practice. In addition, these movements generate a high speed of execution and require inter- and intra-muscle coordination [11].

6.8. Exercise intensity

The load to be used during training intended for muscle power development is another point of discussion. In general, athletes begin to perform exercises with more intense loads and as training progresses, they use lighter loads and less training volume [160,161,165]. This strategy aims to create the necessary conditions for the manifestation of the best performance during the competition. Muscle power is highly dependent on the athlete's ability to develop a high amount of force, and this is evident from studies that show a strong positive correlation (r = 0.77 to 0.94) between peak power and maximum strength [166].

Training for muscle power at high loads is based on the principle of size. This principle is based on the size or caliber of the motoneuron, it is said that the fibers innervated by low-caliber neurons are activated earlier than the high-caliber neurons [167]. Additionally, on the lack of specificity regarding the speed of execution of the movement, it has been said that athletes should have the intention of performing the movement quickly, even if this does not happen [29,168,169]. Exercise performed in this way can improve muscle power [29]. However, the results are still controversial in the literature [29,168,169]. This difference can perhaps be attributed to the characteristics of the movements used in the studies. Punches and kicks are complex, multi-articular movements [29] and require greater motor coordination than the mono-articular movements of plantar back flexion, which was the movement used in the study in which there was an improvement in muscle power in these training conditions [168].

Training using lighter loads or intensity is based on the specificity principle, assuming that athletes can obtain better results if they train with loads with which they generate the greatest muscle power. In this sense, winning karate athletes differ from defeated athletes by generating higher muscle power with lighter loads (30% of 1RM), but not with the use of slightly higher loads (60% of 1RM) [74].

An aspect that should be considered when choosing the intensity used, in addition to the phase of the periodization in which the athlete is, is that if the strength component is prioritized the improvement will occur in the portion of the force in the force-velocity curve. If the velocity is prioritized, the improvement will occur at the portion of velocity in the force-velocity curve. And finally, we can suggest that the use of the optimal load to improve the portion of maximal power in the force-velocity curve. This load improves maximum strength too, but to a lesser degree compared with percentages closer to the maximal loads [59,170].

Another strategy suggested for the development of muscle power is the training with mixed intensity stimulus [4,11,171]. If we imagine that the use of high loads will further affect the portion of the force and that lower loads will affect the speed portion of the force-velocity curve more, we may suggest that training with mixed loads over a period will also be beneficial for the development of power muscular. Harris et al. [172] compared loads that maximized force (80% of 1RM), loads that maximized muscle power generation (30% of peak isometric force), and the combination of both for lower limbs training. After twelve weeks of training, the group that utilized loads that maximized muscle strength did not improve performance during the vertical jump (cm), average vertical jump power (W), peak vertical jump power (W), or standing long jump (m). However, for training loads that maximized muscle power generation and the group that used combined loads, the peak vertical jump power (W) (2.5% and 2.6%, respectively) and vertical jump (2.3 cm and 1.8 cm, respectively) were improved.

In any case, it is necessary to use exercises with different characteristics throughout the competitive season. This is because muscle power is dependent on the integration between force and velocity. In this way, the athlete can improve his performance if there is an improvement in one or both of these characteristics. At the beginning of the season, the athlete can benefit from the use of exercises that generate higher muscle power with higher loads, such as the power clean and the hang power clean, and later use the exercises that generate greater muscle power with intermediate loads or as in the case of squat and jumping exercises respectively. Or even work with a greater range of intensity in a given exercise. For example, perform the squat exercise with intensity between 40% and 70% of 1RM (percentage in which the highest power is generated in that exercise).

An alternative is to work simultaneously with different exercises at different percentages of 1RM. For example, in Table 9 it is suggested to perform exercises with different characteristics and intensities, which will emphasize different portions of the force-velocity curve.

Table 9: Example of exercises performed with different intensities and the emphasis given in the force-velocity curve (Adapted from Haff and Nimphius [170]).

Exercise	Series x Reps	Load (% de 1RM)	Emphasis
Power clean	3 x 5	75-85	Strength
Back Squat	3 x 5	80-85	Strength
Jump Squat	3 x 5	0-30	Velocity
Drop Jump	3 x 5	0	Velocity

Finally, it is expected that athletes will be able to transfer the achieved performance and generate the greatest muscle power during the performance of a specific gesture. The explanation for expecting this effect is that if during planning the two portions of the force-velocity curve are stimulated both will be improved [101,172–179]. Another practical application is that specific movement has a specific coordination and therefore should be introduced in strength-training to improve power in sport-specific actions.

6.9. Repetitions, number of sets, intensity and rest interval between sets and exercises

The production of muscle power is associated with the quality with which each repetition is performed [180]. Traditionally, it is recommended to perform 3 to 6 sets and 1 to 8 repetitions of a given exercise in training sessions designed to develop muscle power [17,18,160,161].

Initially, the effect of the number of sets, repetitions and the way in which they can be performed aiming the development of muscle power will be approached. In general, the sets are a group of repetitions, carried out without interruption, that is, without rest. In turn, repetition is defined as the execution of a complete movement, concentric and eccentric phases, of an exercise. To date, all studies conducted with combat sports athletes have used this configuration of repetitions and sets for the development of acute [15,16] and chronic muscle power [28,91]. It has been observed that increasing the number of repetitions results in higher concentrations of blood lactate [181] (Figure 20). Increased blood lactate is associated with the increase of the hydrogen ions (H+), which is indicated as one of the causes of fatigue [182–184]. However, it does not seem to affect the manifestation of muscle power during the match [36,46,48,49,52]. But the temporal structure seems to be important so that powerful techniques can be carried out for a longer time, as it will be necessary to recover or to avoid the depletion of the energy supplies to continue the task so that the gesture is executed in perfect conditions and with power.

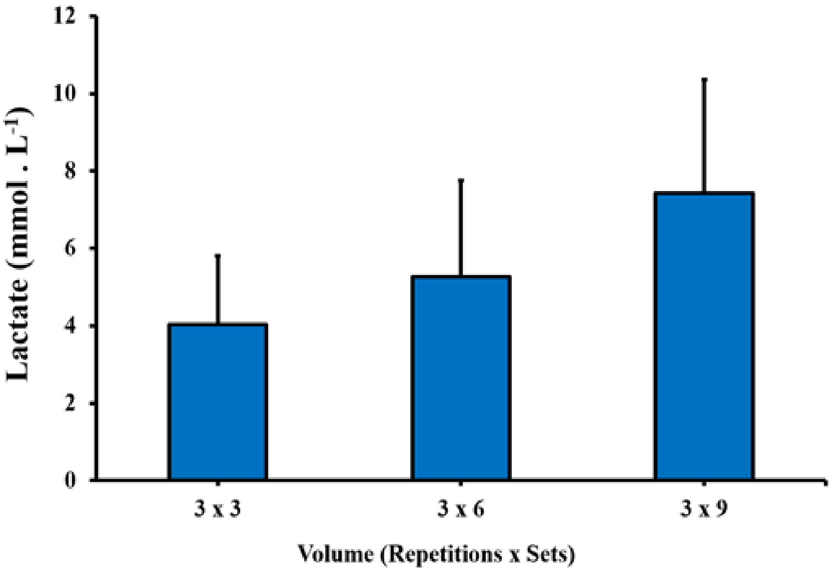


Figure 20: Accumulation of lactate in the power clean exercise according to the volume (Adapted from Date et al. [181]).

Some recent studies have suggested that the use of new methods for performing repetitions within the same sets may alter the performance of athletes wishing to develop muscle power [180,185–187]. Based on some scientific evidence, it is possible to suggest that the performance of sets with inter-repetition intervals and sets with clustered repetitions could benefit athletes who practice sports in which the ability to perform movements with muscle power is important [180,188], as is the case of combat sports. The effect of introducing pause between repetitions between equated sessions regarding volume, intensity and total rest was investigated in judo athletes [189]. Two groups were compared, one which trained up to set failure and another with no failure. The set failure group executed 3 sets to failure of parallel back squat with 4 repetitions at maximum load, and a rest of 3 min between the sets. The no set failure group performed the same but total resting time was distributed among individual repetitions. The authors reported that the no set failure group showed an 18.94% (~17.98) higher average mean propulsive velocity during the session (0.42 ± 0.04 vs. 0.35 ± 0.08 m.s-1), lower blood lactate concentration after session (maximum average value 1.52 ± 0.77 vs. 3.95 ± 1.82 mmol/L-1) and higher mean propulsive velocity with load corresponding to maximum propulsive power (mean propulsive velocity immediately after session 0.64 ± 0.09 vs. 0.59 ± 0.12 m.s-1) compared with the set failure group [189]. Therefore, the distribution of rest interval between repetitions can change the performance of judo athletes using same total rest interval and equated volume.

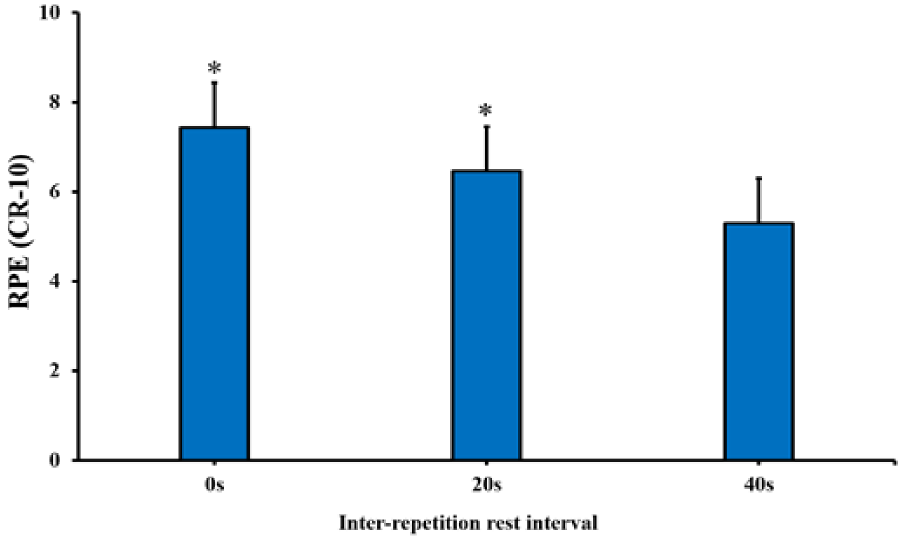


Figure 21: Rating of perceived exertion after the traditional sets and inter-repetition interval (Adapted from Hardee et al. [188]).

As the ability to generate muscle power goes down rapidly after performing few repetitions, something between 5-9 repetitions [180,190], it is likely that performing sets with inter-repetition interval and cluster will generate less muscle fatigue. In addition, the reduction of phosphocreatine (PCr) stores is less pronounced during the inter-repetition and cluster sets when compared to the traditional sets. In addition, it is possible that the intervals used between each repetition or between each cluster allow some recovery of the PCr stores and, consequently, an increase in performance related to the generation of strength and muscle power. In Figure 22, 23 and 24 we can compare a theoretical model of what can happen with the generation of muscle power after the execution of the traditional and cluster sets [185]. Unlike the traditional sets, the cluster-type sets provide some time intervals between the repetitions or grouped repetitions, usually something between 5s and 45s [186,187]. For example, the athlete performs 6 repetitions with 60% of 1RM with the 20s of interval every two repetitions, as shown in Equation 1. We can use the same example by changing the intensity and using percentages of body mass for the prescription, according to the information presented in Equation 2. This type of training may be adequate in some moments of the physical preparation process of the athletes when performing the exercise with reduced fatigue is desirable [180,186,187]. It has been mentioned that exercises using cluster sets generate less fatigue by allowing some muscle metabolic recovery. This process can result in training sessions with the accomplishment of technically more appropriate gestures when compared to the exercises performed in a fatigued condition.

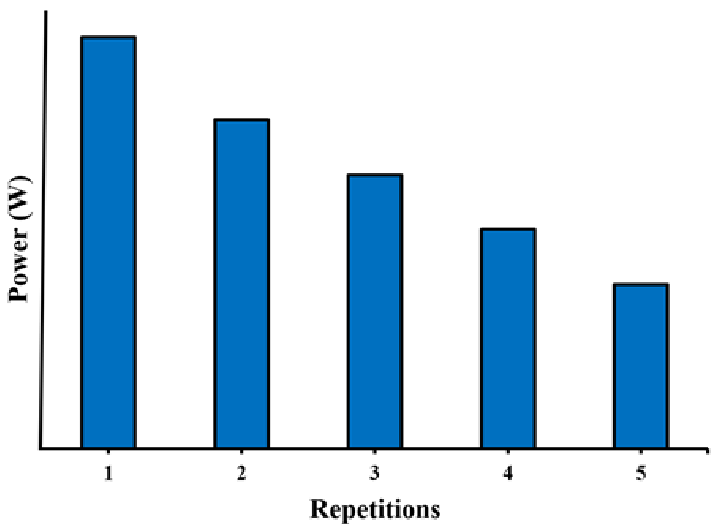


Figure 22: Theoretical model of muscle power generated during traditional sets (Adapted from Haff et al. [185]).

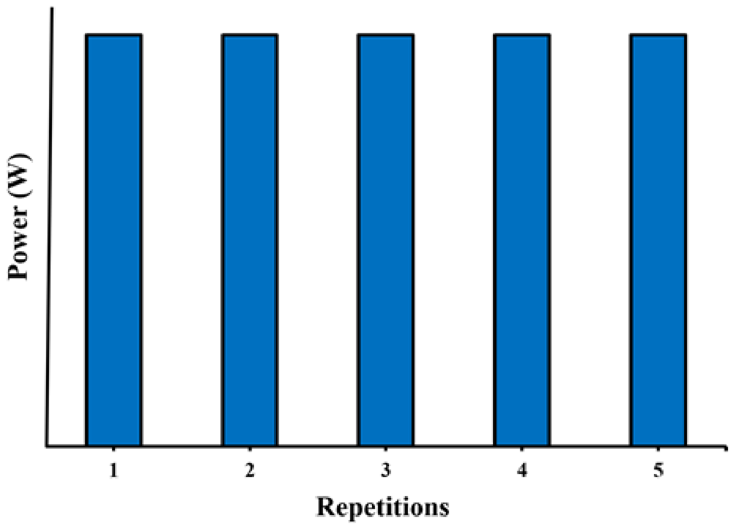


Figure 23: Theoretical model of muscle power generated during cluster sets (Adapted from Haff et al. [185]).

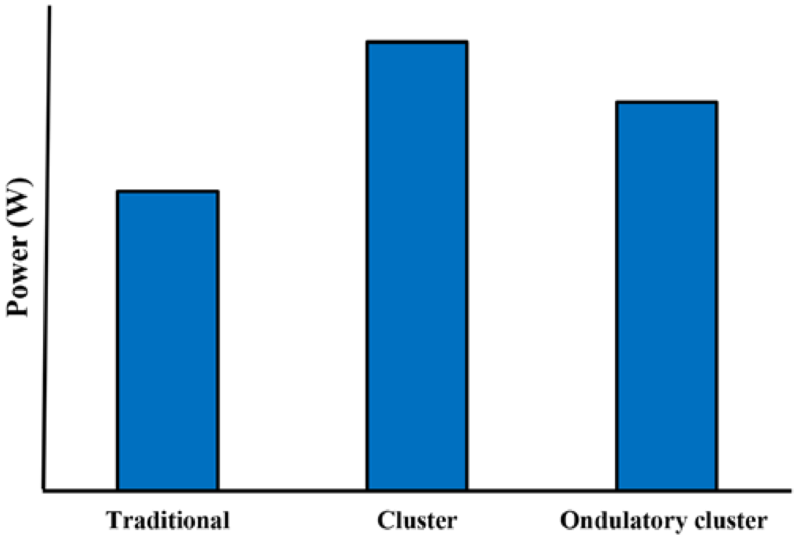


Figure 24: Theoretical model of muscle power generated during traditional, cluster and undulating cluster sets (Adapted from Haff et al. [185]).

$$\frac{\text{6 repetitions}}{\text{2 repetitions by cluster}} = \frac{60\%}{2} \text{ 20s } \frac{60\%}{2} \text{ 20s } \frac{60\%}{2}$$

Equation (1). Example of training prescription using cluster type sets and percentages of one-repetition maximum (1RM).

$$\frac{\text{6 repetitions}}{\text{2 repetitions by cluster}} = \frac{\text{BM }\%}{2} \text{ 20s } \frac{\text{BM }\%}{2} \text{ 20s } \frac{\text{BM }\%}{2}$$

Equation (2). Example of training prescription using cluster type sets and percentages of the athlete's body mass.

In addition, cluster-type sets can help reduce another problem. Athletes who are divided by weight categories, as in the case of combat sports, generally expect to improve their performance by performing muscle power training. However, in most cases these athletes do not wish to gain weight, resulting from strength training. A large variety can be created when using cluster sets, however, in addition to the standard cluster sets, previously presented, there are other variations denominated as undulatory, increasing and decreasing pyramids. These variations can be applied during the training sessions, with the intention of attending to the oscillations that may occur during a combat.

One possibility of manipulation of the cluster type sets is the undulating sets. In this model, the variation of the load between two or more intensities is foreseen. An example of cluster sets is exemplified in Equation 3.

$$\text{Undulating cluster sets} = \frac{\text{4 repetitions}}{\text{1 repetitions by cluster}} = \frac{30\%}{1}\ 30s\ \frac{40\%}{1}\ 30s\ \frac{30\%}{1}\ 30s\ \frac{40\%}{1}$$

Equation (3). Undulating cluster sets.

The pyramidal cluster sets are performed with an increase in intensity to an apex, stipulated according to the objectives of the training session, followed by a reduction until returning to the load initially used. An example of a pyramidal cluster sets can be seen in Equation 4.

$$\text{Pyramid cluster sets} = \frac{\text{6 repetitions}}{\text{2 repetitions by cluster}} = \frac{35\%}{2}\ 35s\ \frac{40\%}{2}\ 35s\ \frac{35\%}{2}$$

Equation (4). Pyramid cluster sets.

In the ascending model the load increases with each cluster, reaching the highest load at the end of the sets, that is, the last cluster set. An example of ascending cluster sets can be seen in Equation 5.

$$\text{Ascending cluster sets} = \frac{\text{6 repetitions}}{\text{2 repetitions by cluster}} = \frac{35\%}{2}\ 35s\ \frac{40\%}{2}\ 35s\ \frac{45\%}{2}$$

Equation (5). Ascending cluster sets.

The descending load model starts with the highest load and is reduced to each cluster within a set. A descending cluster sets model can be observed in Equation 6.

$$\text{Descending cluster sets} = \frac{\text{6 repetitions}}{\text{2 repetitions by cluster}} = \frac{45\%}{2}\ 35s\ \frac{40\%}{2}\ 35s\ \frac{35\%}{2}$$

Equation (6). Descending cluster sets.

The complex spherical cluster model is presented in the following figure. In this model, the intensity and number of repetitions in each cluster are predicted, as shown in Equation 7.

$$\text{Complex undulating cluster sets} = \frac{\text{6 repetitions}}{\text{2 and 1 repetitions by cluster}} = 6/2 + 1$$

$$\frac{45\%}{2}\ 35s\ \frac{60\%}{1}\ 35s\ \frac{45\%}{2}\ 35s\ \frac{60\%}{1}$$

Equation (7). Complex undulating cluster sets.

The interval applied between the repetitions during the execution of cluster sets varies according to the purpose of the training session and the phase of the periodization in which the athletes are. For example, shorter intervals between one cluster set and another may be more indicated when the purpose of the training session or period is to work the strength-endurance or under the greatest fatigue condition. When the goal is the development of muscle power, longer intervals (30s to 45s) between one cluster set and another may be more appropriate. In Table 10 we can observe inter-repetition interval suggestions during the realization of cluster sets according to the objective. It is worth mentioning that the figures presented in the table are only suggestions, understanding that a great variety of combinations is possible.

Table10: Inter-repetition interval suggestion according to the training objective (Adapted from Haff [186]).

Interval between-repetitions	Purpose
5-15s	Strength and muscle power endurance
15-30s	Development of muscle power
30-45s	Maximal muscle power

In a recent study, Moreno et al. [180] had the objective to investigate the effect of the use of cluster type sets compared with the traditional sets. Sets with a total volume of 20 repetitions of a plyometric exercise were performed, applying the recovery interval in different ways regarding the interval duration and clustering the repetitions, as presented in Equation 8. They demonstrated power maintenance, take-off velocity (TOV) and jump height with the accomplishment of the cluster set 2 followed by a rest interval of 10s. Therefore, this may be a good strategy when the goal is to develop muscle power with the use of plyometric exercises.

2 sets x 10 repetitions / 90s of rest interval between sets

$$\frac{20\ \text{repetitions}}{5\ \text{repetitions by cluster}} = \frac{BM}{5}\ 30s\ \frac{BM}{5}\ 30s\ \frac{BM}{5}\ 30s\ \frac{BM}{5}$$

$$\frac{20\ \text{repetitions}}{2\ \text{repetitions by cluster}} = \frac{BM}{2}\ 10s\ \frac{BM}{2}\ 10s\ \frac{BM}{2}\ 10s\ \frac{BM}{2}\ 10s\ \frac{BM}{2}\ 10s\ \frac{BM}{2}\ 10s\ \frac{BM}{2}\ 10s\ \frac{BM}{2}\ 10s\ \frac{BM}{2}$$

Equation (8). Experimental design used by Moreno et al. [180].

Although we are not aware of any studies that have used cluster-type sets to develop muscle strength and power in the training of athletes involved with combat sports, this form of training could be used during sessions, aiming at the development of muscle power and technical quality of execution of the movement [2,191]. In general, it seems that the use of cluster sets is more adequate when the development of muscle power is the main objective. Traditional sets are preferable if the goal is to generate greater muscle hypertrophy or higher levels of maximum strength.

6.10 Rest interval between sets

The execution of multiple sets has been demonstrated to be superior to the execution of a single set for the strength and power development [192,193]. However, the execution of multiple series depends on the athlete's ability to perform the movement with good quality, in a consecutive way. The ability to sustain the execution of multiple sets is dependent on the time interval applied between the sets. The duration of the recovery interval between the sets allows recovery of the energy systems (e.g., adenosine triphosphate [ATP] and PCr), allowing recovery for the production of muscle strength [194,195].

The recovery interval applied between sets depends on the purpose of the training. In general, intervals between 2-8 minutes between sets are recommended when the training session aims to train muscle power [160,161,196,197]. However, it is worth noting that in addition to the training objective, other factors should influence the coach's decision on the interval to be applied.

7. Final considerations

In this chapter, suggestions were presented for the development of training aimed at developing muscle power for combat sports athletes. In this sense, several means and methods were approached in order to extend the possibilities of application, as well as the specificity of the training session. For highly trained athletes it is important to consider the specificity of the modality so that the athlete improves muscle power in a specific gesture. Among the means and training methods presented, it seems that those involving ballistic, elastic and complex gestures cause positive changes by using technical gestures with the same pattern of movement. However, the development and possibility of transfer of muscle power should be further investigated in the future.

Conflict of interest

None declare.

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CHAPTER 5
Developing strength-endurance for combat sports athletes

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Abstract
Strength-endurance is one of the trainable physical capacities that could determine the success in some combat sports and its inclusion is obligatory in the training periodization of high-level athletes. In striking combat sports, such as boxing and taekwondo, it seems likely that increases in dynamic strength-endurance improve the ability to execute combat movements repeatedly. On the other hand, grapplers need to develop high levels of strength-endurance because during the match much time is spent in grip dispute and the success in this phase may determine the possibility to execute scoring techniques. Furthermore, in mixed combat sports, where a combination of striking and grappling are required, athletes needs to have the capacity to maintain dynamic or static muscular actions during prolonged periods during the match, and the strength-endurance is one key element. Therefore, this chapter presents the strength-endurance requirements during the match, the specific tests for its evaluation, scientific evidence of longitudinal studies on the development of strength-endurance in combat sports athletes and the methods for its development.

Keywords: Martial arts; combat sports; muscular endurance; training; performance; core zone.

1. Introduction

Strength-endurance is one of the trainable physical capacities pertaining to the necessary requirements for the sports performance, and its inclusion is obligatory in the training periodization of high-level athletes [1]. Strength-endurance is characterized by the ability of the individual to perform a certain number of repetitions of an exercise or a technical gesture during a certain period or until the failure, by the time of maintenance of a certain movement in the same prescribed rhythm and with the same efficiency [2], or by the ability to develop strength for a prolonged period and maintain a high-intensity muscular effort between thirty seconds and two minutes [3].

For Martin et al. [4], strength-endurance performance depends on two fundamental characteristics, which would be the maximum force - related to the domain of a particular load and the duration of the domain of this load - that would depend on the performance of the metabolism of the musculature in terms of energy transfer. Thus, the longer the tension time with a certain load that promotes the increase in muscle fatigue, the better the gains in relation to strength-endurance due to the great metabolic mobilization [5].

Each sport has its particularities that determine the types of strength that are most required. In countless sports, strength-endurance is one of the physical capacities that determine success, as in the case of some combat sports, especially those of grappling [6].

In striking combat sports, as in the case of boxing, it seems likely that increases in dynamic strength-endurance improve the boxer's ability to execute combat movements repeatedly, such as, for example, the direct and the cross, which are attack movements, influencing the number of hits made, and consequently the score of points in favor of the attacker [7,8].

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In judo, a grappling combat sport, which intends to keep the opponent under control, dominating the distance between them, and thus throw the opponent down, the athletes need a combination of maximum strength and strength-endurance during the match. In fact, strength-endurance differences, with the objective of performing the movements of pulling and pushing more effectively, can influence and be potential predictors of performance in judo [9].

On the other hand, for wrestlers who execute grappling techniques like the clinch (i.e., control of the adversary's neck and head using the arms), such measures can provide useful information in relation to individual performance parameters [3], both in Greco-Roman and freestyle [10,11].

In mixed combat sports, such as mixed martial arts (MMA), where striking techniques are used with arms and legs, and predominantly with the upper body, the ability to maintain dynamic or static muscular actions for prolonged periods during a combat resisting to the fatigue is also a relevant physiological characteristic, and it is desirable that the athlete presents high levels of strength-endurance for success in this modality [12].

Therefore, in this chapter, we will discuss strength-endurance and its application, the responses of this variable during the matches, the specific tests for its evaluation, the scientific evidence of longitudinal studies on the development of strength-endurance in combat sports athletes and the methods for its development.

2. Strength-endurance response during striking and grappling matches

Knowing the response of a certain physical capacity, whether neuromuscular or metabolic, during a simulated match or a competition is important to identify the athlete's behavior and determine its degree of influence on the success of the modalities. Therefore, based on its determination, coaches and/or physical trainers can periodize the training more consistently.

2.1. Striking Combat Sports

In simulated matches (S) or official competition (O), karate athletes use upper body (S = 73.2 ± 24.4%; O = 73.2 ± 19.6%) and lower body (S = 26.8 ± 19.6%; O= 26.8 ± 24.4%) to attack and counter-attack. Both attack and counter-attack actions are mainly executed with the upper body (Table 1) [13].

Table 1: Percentage of upper and lower body karate techniques according to karate combat conditions (adapted from Chaabène *et al*. [13]).

Situation		Attack (%)	Counter-attack (%)
Simulated condition	Upper body	54.6 ± 28.9	84.9 ± 26.6
	Lower body	45.4 ± 28.9	15.1 ± 26.6
Official condition	Upper body	63.1 ± 23.7*	82.7 ± 32.8
	Lower body	36.9 ± 23.7	17.3 ± 32.8

*= significantly different (P <0.05) from simulated combat condition; the values are presented as mean ± standard deviation.

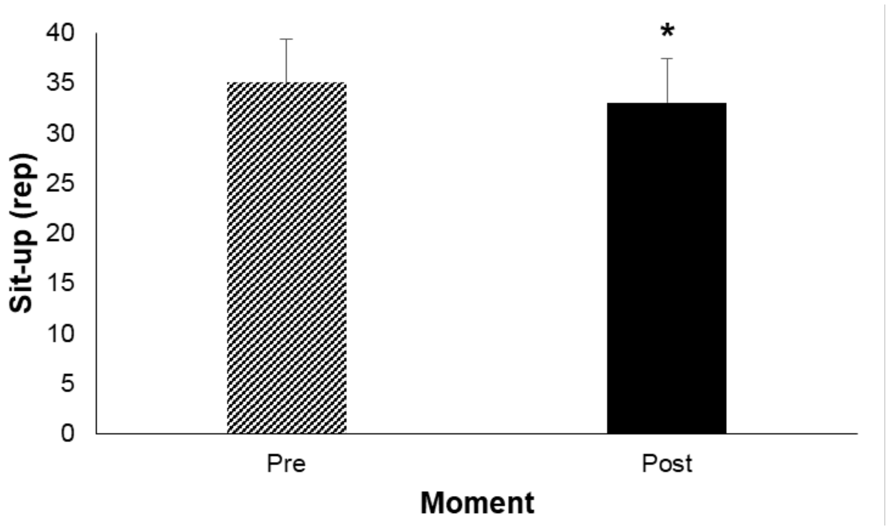
However, regardless of the predominance of the upper body for these actions, when evaluating the rating of perceived exertion in specific areas of the body (LRPE), Chaabène *et al*. [13] identified that after simulated and competition match conditions, karate athletes presented greater perceived effort in the lower-body (Table 2), suggesting that the musculature of this region was more requested during the combat in terms of strength-endurance, and that the training should be aimed at improving these muscle groups with the goal of delaying fatigue and allowing the athletes to perform combats with a better performance.

In a study conducted with Muay-Thai athletes to identify the acute effects of a combat on general strength indicators, Mortatti et al. [14] identified that after a ten 3-min rounds match, with rest intervals of 1 minute between rounds, the athletes had a reduction in the ability to execute sit-ups in 30s (Figure 1).

Table 2: Local of higher rating of perceived exertion in simulated and official competition conditions (adapted from Chaabène *et al*. [13]).

	Muscle	LRPE-S (%)	LRPE-O (%)
Upper body	Deltoid	4.76	0
	Triceps	9.52	0
	Biceps	9.52	7.69
	Forearms	4.76	0
Lower body	Quadriceps	23.81	30.77
	Hamstrings	19.05	23.08
	Triceps sural	28.57	30.77

LRPE = local rating of perceived exertion; S = simulated condition; O = official condition.



* = significantly different (P < 0.05) de pre-match.

Figure 1: Repetitions in a sit-up test before and after a Muay-Thai match (adapted from Mortatti *et al*. [14]).

2.2. Grappling Combat Sports

In wrestling, pulling, pushing and stabilizing the opponent using the upper body and trunk, as well as lifting the opponent using the legs are movements that occur regularly during a match [15]. Therefore, all the attack actions used in the Greco-Roman and freestyle wrestling are preceded by the control of the adversary, by means of control of support points to execute the throwing techniques (e.g., upper-body, head, waist, lower-body), resulting in a high demand for upper-body and trunk muscle groups strength-endurance [16,17].

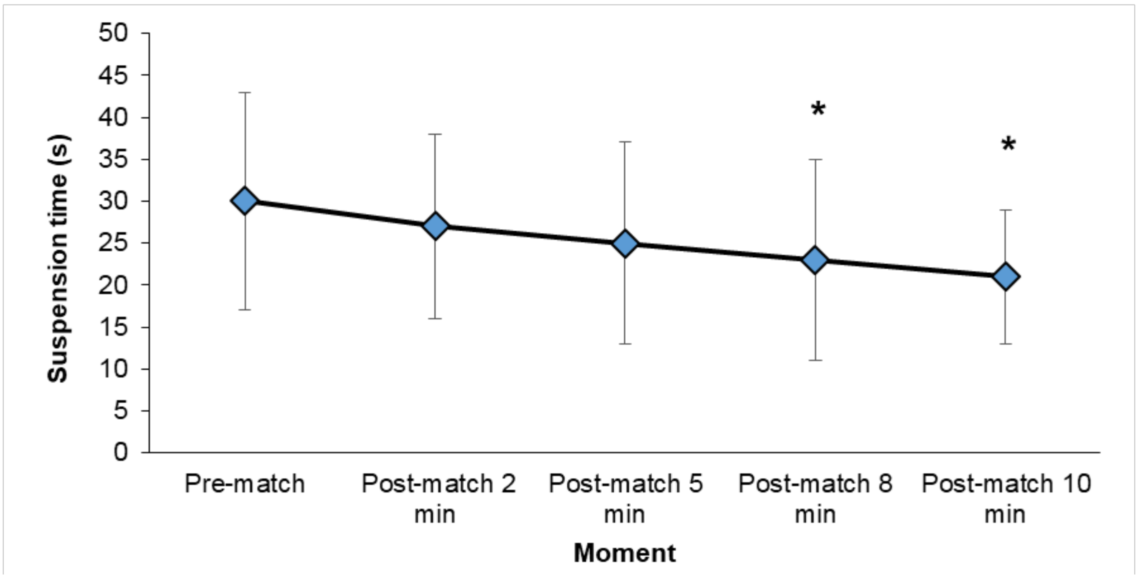
In fact, these motor actions performed repeatedly during a combat or in a competition can promote a certain degree of fatigue and affect strength-endurance capabilities, as demonstrated by Nilsson et al. [18], in reporting fatigue in specific muscles perceived by the athletes who participated in the Greco-Roman Wrestling World Championship, which was especially high in the anterior region of the forearm and in the anterior deltoid.

In a judo match, the actions can be developed both in standing (*tachi-waza*) combat and on the ground (*ne-waza*). Most of the match time during stand actions is spent in grip dispute (14 ± 15s), corresponding to 58% of the standing combat time and 28% of the total combat time - including the pauses – [19], which requires a great upper-body isometric and dynamic strength-endurance with an emphasis on the forearm muscles [20]. In addition, immobilization actions on the ground also require this capacity [21].

In order to verify the effects of judo matches with different durations (1, 2, 3, 4 and 5 min) on upper-body dynamic strength-endurance, Julio et al. [22] assessed twelve male judo athletes who performed the dynamic strength-endurance judogi chin-up test before and 6 minutes after each match. The results demonstrated that upper-body strength-endurance was reduced after match when compared with pre-match values. However, there was no effect of match duration on upper-body strength-endurance.

Moreover, Kons et al. [23] revealed that medalists and non-medalists in an official tournament did not differ concerning the rating of perceived local exertion, but both groups reported higher values for upper-body compared to lower-body. Medal winners reported the fingers, abdomen and anterior tibia as the most cited areas, whereas non-medalists reported the forearms and fingers as the most cited areas presenting muscle fatigue after the matches.

Investigations conducted with Brazilian jiu-jitsu athletes analyzed the isometric strength-endurance response in Brazilian jiu-jitsu matches with varied durations (2, 5, 8 and 10 minutes) [24], and in simulated competition [25]. In matches lasting 8 and 10 min, isometric strength-endurance post-match decreased when compared to pre-match (Figure 2). Differently, in simulated competition there were no significant differences for the values pre and post-matches (Figure 3).



Pre-match: values mean of pre-match of 2, 5, 8, and 10 min matches. * Significantly different from pre-match (P < 0.05).

Figure 2: Suspension time in the kimono grip isometric strength-endurance test before and after Brazilian jiu-jitsu matches with varied durations (adapted from Andreato et al. [24]).

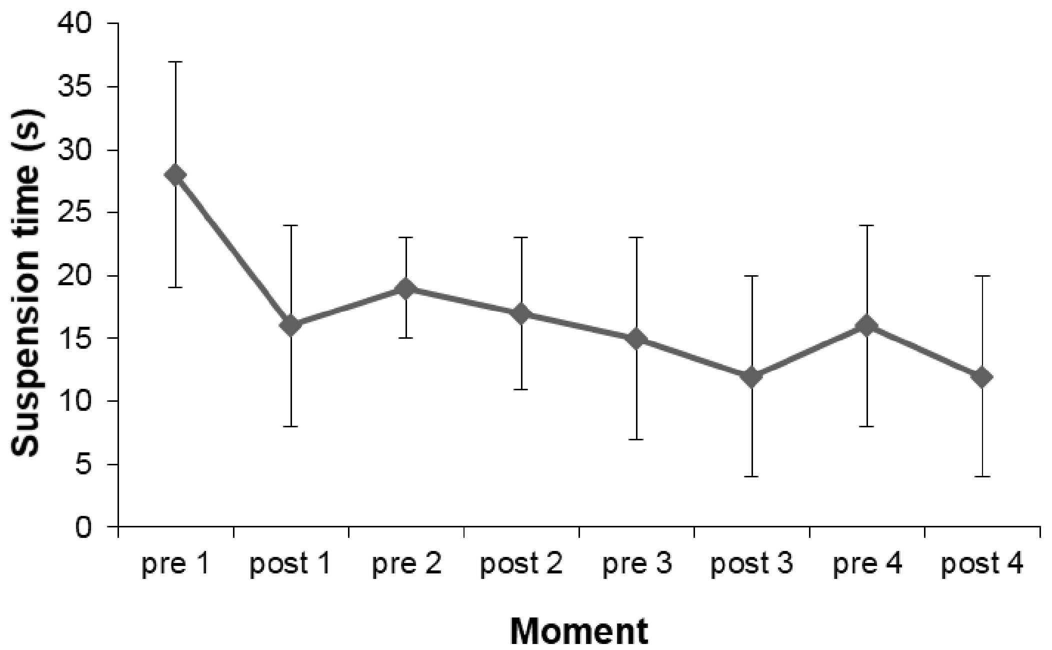


Figure 3: Suspension time in the kimono grip isometric strength-endurance test during a simulated Brazilian jiu-jitsu competition (adapted from Andreato et al. [25]).

When the upper-body isometric strength-endurance response after a 10-min duration Brazilian jiu-jitsu match simulation was examined, Silva et al. [26] found a decrease in upper-body strength-endurance performance in the suspension time in the kimono grip isometric strength-endurance test (pre= 65.5 ± 16.78 s; post = 49.75 ± 15.01 s).

Detanico et al. [27] analyzed the effect of a Brazilian jiu-jitsu simulated tournament on strength parameters. Twenty-two non-advanced male Brazilian jiu-jitsu athletes participated in a simulated tournament consisting of three 7-min matches separated by 14 min of passive rest. Athletes showed a significant reduction in the number of repetitions in the kimono grip dynamic strength-endurance test (pre-match = 11 ± 4 rep.; post-match 1 = 8 ± 4 rep.; post-match 2 = 7 ± 3 rep.; post-match 3 = 7 ± 3 rep.). Authors concluded that a simulation of a Brazilian jiu-jitsu tournament generated a decrease in upper-body strength-endurance performance.

No studies were found that examined the influence of a MMA match on strength-endurance performance.

3. Test for strength-endurance assessment in combat sports athletes

The characterization of the physical fitness of an athlete, the evaluation of the effects of a training period on a given physical capacity or even the classification of athletes by their level of sporting excellence (e.g., elite or non-elite), can be done through the application of physical tests, and the more specific to the reality of combat sports are the protocols, the more reliable will be the evaluation of the combat sports athletes. Although there are specific tests for some combat sports, no indexed publications were found that report specific tests for mixed modalities. In any case, given the characteristics of these modalities, it is possible to adopt the proposed tests for grappling and striking combat sports to mixed combat sports.

3.1. Striking combat sports

A battery of tests to evaluate the physical fitness of male Kyokushin karate athletes was proposed by Sterkowicz and Franchini [28]. Among the different tests presented, for the purpose of evaluating upper-body strength-endurance, clapping hand push-ups in the concentric phase of the movement was used.

As clinch occurs frequently during matches in this modality, the authors presented these specific fighting situations to justify the use of a test that assesses the local muscular endurance and established some reference points (Table 3), considering the number of repetitions performed frequently in the test. These values could be used to compare the individual performance of an athlete or to make comparisons between athletes.

Table 3: Performance classification according to clapping hands push-ups (adapted from Sterkowicz and Franchini [28]).

Classification	Push-ups (n)
Excellent	≥44
Good	31–43
Regular	25–30
Poor	10-24
Very poor	≤ 9

Taekwondo can be distinguished from other combat sports since its main focus is the kicking techniques, so during a match, numerous strikes are carried out with the legs against the thorax and the head of the opponents, which implies explosive movements like jumps and turns with changes of direction. The kicks correspond to 100% of all the techniques that were used to score points in an Olympic competition [29], and this can contribute to the appearance of fatigue in the lower extremities due to the number of strikes that are carried out during the match, influencing thus the sport performance [30]. It is important to note that after the introduction of the electronic body protector, some points have been obtained through punching techniques.

However, although the main focus is on the lower extremities due to the ability to apply kicks, studies can be found in the literature that attempted to analyze both upper-body and abdominal muscles strength-endurance, since athletes can use the upper-body to execute punches against the trunk of the opponent, and mainly to defend themselves, avoiding that the opponent scores. In this way, trunk muscles are involved in various taekwondo movements, such as turning kicks, and in the absorption and assimilation of the impact suffered in the trunk by the strikes received during combat [31].

For example, in order to evaluate the strength-endurance of female Croatian taekwondo athletes, and compare them to each other, based on sports success, Markovic et al. [32] evaluated 13 athletes divided into two groups using push-ups and sit-ups in 60 s tests. The authors did not find any significant differences between the groups for both tests and suggested that upper-body muscle endurance seems to be of less importance for taekwondo performance, but that abdominal strength-endurance may be of some importance.

In another study, which aimed to evaluate and compare Malaysian taekwondo athletes' motor skills in the junior (n = 10) and adult categories (n = 10), Suzana and Pieter [33] did not identify any differences in the number of repetitions in the 60s sit-up test between athletes in the adult and those in the junior categories.

Although these tests are general and not combat-specific, this protocol of assessment for upper extremities and trunk seems to have a good acceptance by investigators as a method to analyze strength-endurance of taekwondo athletes, since similarly, it was adopted by Antunez et al. [34] to evaluate high-level athletes, which corroborates the findings of Markovic et al. [32] because these authors concluded that elite taekwondo athletes have well-developed abdominal endurance. Table 4 shows some of these results.

Table 4: Strength-endurance in push-up and sit-up tests in taekwondo athletes (the values are presented as mean ± standard deviation or mean and amplitude).

Study		Push-up (rep in 60s)	Sit-up (rep in 60s)
Markovic *et al.* [32]	Elite (Female; n=6)	25.8 ± 8.5	58.7± 7.0
	No elite (Female; n=7)	23.1 ± 7.7	52.2± 3.5
Antunez *et al.* [34]	(Male; n=7)	60.57 ± 13	54.14 ± 5.24
Suzana and Pieter [33]	Junior (Male; n=10)	—	39.50 (36.75 – 43.00)
	Adult (Male; n=10)		33.50 (29.50 – 40.25)

In an attempt to assess the lower-body fatigue index of taekwondo athletes, Valente et al. [30] used a test based on the analysis of vertical jumps, which had as protocol the execution of 4 sets of 15s of intermittent jumps in a contact platform. Based on the literature, the authors of this study suggested that the measurement of vertical jump height is of great interest, since with this measure the fatigue index can be estimated, and from the time of flight and the number of jumps made in a certain set in a time interval, it is possible to obtain the degree of reduction of the strength-endurance capacity and the maintenance of sports performance.

The equations used to evaluate the performance in the test are proposed by Bosco et al. [35] and are described below:

$$\mathbf{MP = (g^2 * Tt * 15) / (4.n) * (15 - Tt)}$$

Where, MP = Mean power output (W/kg); g = Gravity acceleration (9,81m/s^2); Tt = Total flight time (ms); and *n* = Number of jumps.

$$\mathbf{FI = PP\ (45\text{-}60) / PP\ (0\text{-}15)}$$

Where, FI = Fatigue index (%); PP (45-60) = Average power output in the last set of 15s (W/kg); and PP (0-15) = Average power output in the first set of 15s (W/kg).

The authors identified a high fatigue index (FI = 81 ± 12%) in the test. However, they suggested that since the maximum intensity of effort during the 4 sets of 15s of jumps cannot be controlled directly during the execution of the test, this could be a limitation of the protocol.

3.2. Grappling combat sports

The specific motor actions in wrestling are incorporated in a test proposed by Utter et al. [36], in which throwing exercises are carried out such as those performed during combat. The protocol consists of the execution of five repetitions of five technical movements used during the match in a circuit, being three exercises only of freestyle and two that can be used both in freestyle and Greco-Roman wrestling. The test runs in pairs and the participants must be of the same weight category, one of the athletes will be the performer and the other will only receive the actions, which allows the performer to execute all movements, returning as soon as possible to the initial position to allow the performer's actions at their maximum pace. The techniques used were double-leg takedown, single-leg takedown, fireman's carry, stomach-to-back lift, and hip toss. The count of the time starts at the order of "go" of the evaluator, the performer must execute the 5 repetitions of the first movement and then move on to the next, at the end of the fifth repetition of the fifth exercise the time will be recorded. The classification of the fitness level of the athlete evaluated is related to the time necessary to execute the 25 repetitions and the shorter the time the better is the conditioning of the wrestler. The number of repetitions executed and the time used in the test could be used as a tool for the evaluation of specific strength-endurance in both wrestling styles. However, general classification tables are not available by class, gender, and weight category.

Upper-body strength-endurance is a determining factor for sporting success in judo since the action of gripping the judogi of the opponent and its maintenance during combat is related to the outcome of the match [37]. To assess this physical capacity in judo, two specific tests for judo athletes were proposed by Franchini et al. [38]. The tests are related to the upper-body isometric handgrip and dynamic strength-endurance. One test analyzes the maintenance time executing the judogi grip, whereas the other analyzes the number of repetitions of the exercise in the dynamic chin-up executed with the judogi grip. The performance of the isometric test, represented by the time of suspension gripping the judogi was correlated with the maximum handgrip isometric strength relative to the body mass (r = 0.73) and with maximal strength (1RM) in a seated row exercise relative to body mass (r = 0.71). In turn, the performance in the dynamic test, represented by the number of chin-up repetitions gripping the judogi, was correlated with the maximum isometric handgrip strength relative to body mass (r = 0.86), with the maximum strength in seated row (1RM) relative to body mass (r = 0.81) and the upper-body Wingate test mean power (r = 0.69). These results indicate that the two tests have a good relationship with the tests commonly used to determine both maximal isometric strength (handgrip), as well as maximal dynamic strength (1RM in seated row) and variables associated with muscle strength. In addition, the results of both chin-up tests also correlated (r = 0.75), indicating that the two tests basically evaluate the same variable, and can be used to evaluate strength-endurance with the use of grip in the judogi, similar to what happens in judo. Another important aspect to consider is that the reliability of the isometric chin-up test gripping the judogi was high (ICC = 0.98) [38].

With the objective of identifying the differences in the upper-body strength-endurance among the Brazilian judo athletes' team and state level athletes, Franchini et al. [9] applied tests of the maximum time of suspension gripping the judogi and the number of repetitions in the chin-up gripping the judogi. No significant differences were found between the groups for the isometric strength-endurance test gripping the judogi. However, for the dynamic strength-endurance test gripping the judogi, the athletes of the Brazilian team performed more repetitions than the state-level team (Table 5).

Table 5: Isometric and dynamic strength-endurance chin-up tests in judo athletes (Adapted from Franchini et al. [9]).

	Maximal isometric time gripping the judogi (s)	Dynamic strength endurance gripping the judogi (rep)
Brazilian team (n=16)	35 ± 18	12 ± 5
Barueri team (n=16)	39 ± 14	9 ± 4*

*$p < 0.05$ vs. Brazilian team.

Recently, studies have suggested classificatory tables for both judogi grip isometric strength-endurance and judogi grip dynamic strength-endurance tests to judo male [39, 40] and female athletes [39, 40] assessed Brazilian athletes from state, national and international levels, between 18 and 40 years old. On the other hand, the study of Agostinho et al. [40] presents data from high-level cadet and junior athletes from Brazil and Serbia. Table 6 summarizes the values presented in both studies.

Table 6: Classificatory table for both dynamic and isometric strength-endurance chin-up tests gripping the judogi.

					LEVEL				
					Very poor	Poor	Regular	Good	Excellent
Dynamic judogi chin-up test	Absolute (reps)	Branco et al. [39]			≤1	2 – 6	7 – 16	17 – 19	≥20
		Agostinho et al. [40].	Male	Cadet (n=80)	≤2	3 – 13	14 – 25	26 – 31	≥32
				Junior (n=47)	≤3	4 – 15	16 – 28	29 – 30	≥31
			Female	Cadet (n=60)	≤1	2 – 5	6 – 16	17 – 22	≥23
				Junior (n=35)	0	1 – 3	4 – 20	21 – 23	≥24
	Relative (reps.kg)	Branco et al. [39]			≤121	122 – 474	475 – 1,190	1,191 – 1,463	≥1,464
		Agostinho et al. [40]	Male	Cadet (n=80)	≤226	227 – 784	785 – 1,737	1,738 – 2,244	≥2,245
				Junior (n=47)	≤411	412 – 1,158	1,159 – 2,026	2,027 – 2,366	≥2,367
			Female	Cadet (n=60)	≤144	145 – 350	351 – 799	800 – 1,142	≥1,143
				Junior (n=35)	≤58	59 – 306	307 – 1,056	1,057 – 1,296	≥1,297
Isometric judogi chin-up test	Absolute (s)	Branco et al. [39]			≤10	11 – 25	26 – 55	56 – 62	≥63
		Agostinho et al. [40]	Male	Cadet (n=83)	≤7	8 – 40	41 – 69	70 – 89	≥90
				Junior (n=43)	≤6	7 – 34	35 – 65	66 – 75	≥76
			Female	Cadet (n=52)	≤12	13 – 26	27 – 55	56 – 74	≥75
				Junior (n=30)	≤2	3 – 17	18 – 57	58 – 71	≥72
	Relative (s.kg)	Branco et al. [39]			≤1051	1,052 – 2,041	2,042 – 3,962	3,963 – 4,008	≥4,009
		Agostinho et al. [40]	Male	Cadet (n=83)	≤626	627 – 2,744	2,745 – 4,506	4,507 – 5,856	≥5,857
				Junior (n=43)	≤822	823 – 3,158	3,159 – 4,732	4,733 – 5,713	≥5,714
			Female	Cadet (n=52)	≤554	555 – 1,514	1,515 – 2,932	2,933 – 3,405	≥3,406
				Junior (n=30)	≤243	244 – 1,232	1,233 – 3,216	3,217 – 3,933	≥3,934

Therefore, judo coaches and strength and conditioning professionals can evaluate their athletes and provide them with a clear comparison with their peers, and use them to evaluate the evolution along the different training phases. It is important to consider that lighter athletes likely perform better in absolute terms (i.e., number of repetitions and time of suspension) whereas heavier athletes present higher values multiplied by their body mass. Therefore, caution is needed when comparing athletes from different weight categories.

Another method was used by Bonitch-Góngora et al. [41], who assessed differences and similarities between young elite judokas and those who were not considered elite in concerning isometric handgrip strength-endurance. Following the test protocol, participants performed 8 sets of 10s of muscle contraction on an electronic dynamometer with 10s passive rest intervals. Seventy-three athletes of both sexes were evaluated. The results suggest that elite judo athletes are able to develop higher levels of handgrip strength and also presented better strategies to maintain successive contractions, which are common actions during the judo match.

Silva et al. [42] conducted a study to evaluate the reliability of two tests to evaluate strength-endurance gripping the kimono grip in Brazilian jiu-jitsu athletes. The tests are the same tests used to evaluate judo athletes [38] and consisted of: a) maximum time of suspension in the chin-up exercise (MSL), with total flexion of the elbow and gripping the kimono rolled around the bar, and b) the maximum number of repetitions (MNR) of complete flexion and extension of elbow in the fixed bar gripping the kimono. For the analysis of reliability of these tests, the athletes were submitted to test and re-test, and the data found in the study allowed to affirm that both tests are reliable for the evaluation of isometric strength-endurance (intraclass correlation coefficient = 0.971 and the limits of agreement = - 6.9 and 2.4s) and dynamic strength-endurance gripping the kimono (intraclass correlation coefficient = 0.987 and the limits of agreement = - 2.9 and 2.3 rep), and can be used to differentiate the jiu-jitsu athletes from different levels (i.e., elite and non-elite) (Table 7).

Table 7: Isometric and dynamic strength-endurance chin-up tests gripping the kimono in elite and non-elite Brazilian jiu-jitsu athletes (Silva et al. [42]).

	Elite (n = 10)	**Non-elite (n = 10)**
MNR (rep)	15 ± 4	8 ± 3*
MSL (s)	56 ± 11	38 ± 11*

*P < 0.05 Non-elite *vs*. Elite. MSL: maximal static lift; MNR: maximal number of repetitions

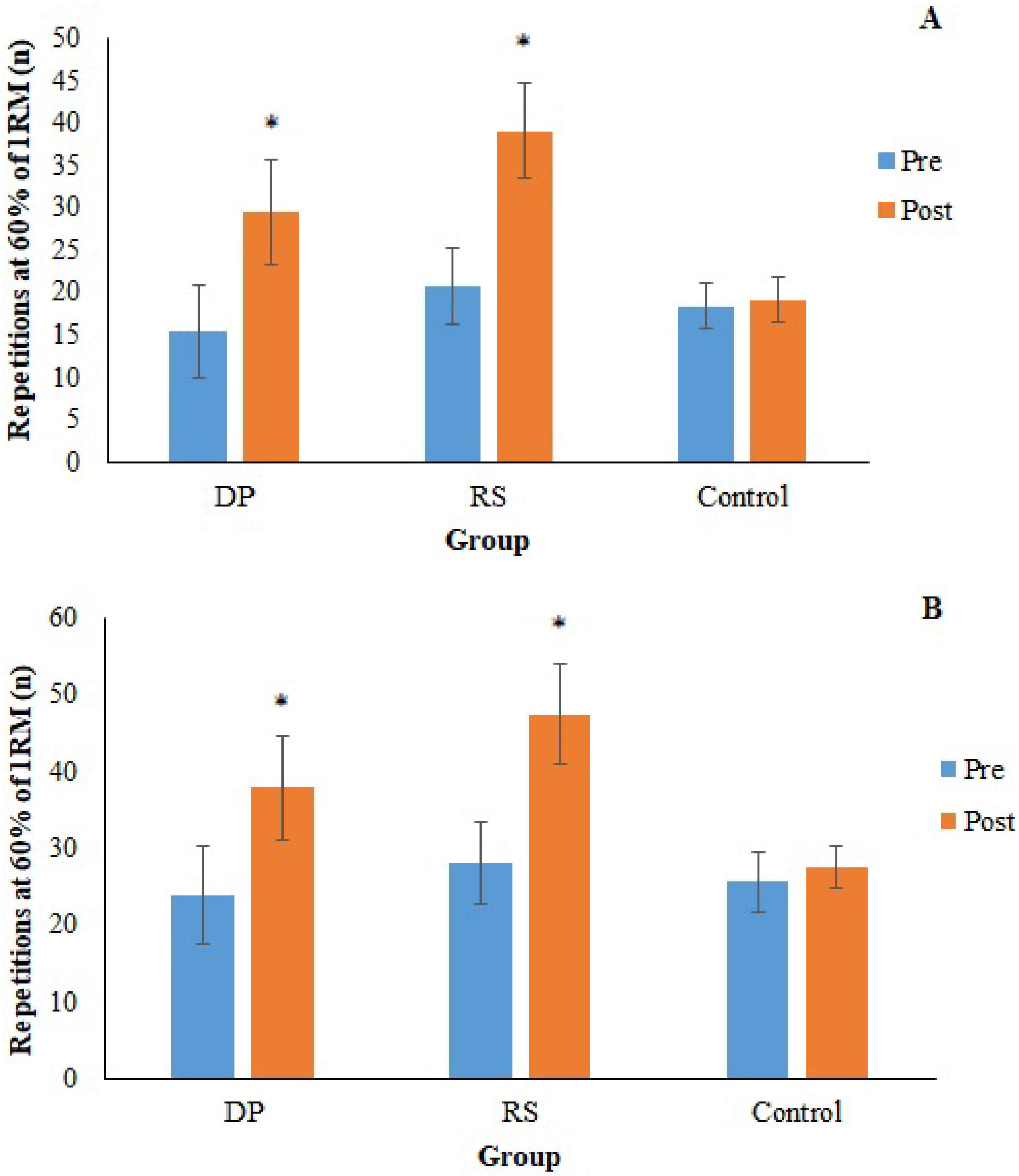
Silva et al. [43] examined if there were differences between Brazilian jiu-jitsu practitioners from different levels (advanced, non-advanced, recreational and beginners), in both isometric and dynamic strength-endurance chin-up tests gripping the kimono. Authors concluded that the isometric strength-endurance chin-up test was able to discriminate isometric strength-endurance between the four levels of Brazilian jiu-jitsu practitioners. However, the dynamic strength-endurance test was able to discriminate strength-endurance only between the groups with larger differences concerning practice levels (advanced and non-advanced versus recreational and beginners).

The assessment of strength-endurance has also been carried out with exercises commonly used in the training process of the combat athletes, using training loads between 60 and 80% of 1 RM [44,45], with comparisons throughout the season or with classificatory tables [46].

4. Longitudinal studies on the development of strength-endurance in striking, grappling and mixed combat sports athletes

Mirzaei et al. [47] evaluated the impact of 4 weeks of training, corresponding to the general preparation phase in physiological parameters of 15 young wrestlers (15.2 ± 0.94 years). Strength-endurance of arms and abdominals was evaluated from a number of repetitions performed in the pull-up (pre: 16.53 ± 9.60 rep, post: 18.66 ± 10.93 rep) and 1-min sit-up tests (pre: 45.66 ± 6.21 rep, post: 48.53 ± 5.24 rep), respectively, but no differences were found between the periods, suggesting that the training was not enough to promote the improvement of this physical capacity in this group.

Another study conducted by Mirzaei et al. [48], with 22 young wrestlers, aimed to investigate the effect of 8 weeks of strength training with two load patterns in strength-endurance of the upper (bench press) and lower body (leg press). The chosen loading patterns were the double pyramid (DP) and the reverse pyramid (RP). For DP loading pattern the athletes performed 4 rep with 80%, 3 rep with 85%, 2 rep with 90%, 1 rep with 95%, 1 rep with 95%, 2 rep with 90%, 3 rep with 85% and 4 rep with 80% of 1RM. RP loading pattern consisted of 2 rep with 90%, 10 rep with 70%, 15 rep with 60%, 2 rep with 90%, 10 with rep 70% and 15 rep with 60% of 1RM. The athletes were divided into three groups: control (C, n = 8), DP (n = 7) and RP (n = 7). The two experimental groups had their training volume equated. The athletes performed a maximal load test for both exercises, and the load corresponding to 60% of 1 RM was selected as a reference for the dynamic endurance test before and after the intervention. As a result, it was found that athletes who performed the training of both load patterns showed an improvement in upper- and lower-body strength-endurance compared to the control group, measured from the number of repetitions in the bench press (Figure 4A) and leg press (Figure 4B) exercises, respectively. However, the authors found no significant differences between the training models used, but both resulted in a greater strength-endurance, which did not occur for the control group. It is not clear, however, if the load used in the post-test is related to the value of 1 RM after training or pre-training, which would undoubtedly influence the result since as the groups increased the maximum strength, the use of pre-training load would represent values lower than 60% of 1RM.



*p < 0.05 pre and post for the same group. DP: double pyramid; RS: reverse pyramid.

Figure 4: Number of repetitions at 60% of 1RM for bench press (A) and leg press (B) in young wrestles (Adapted from Mirzaei et al. [48]).

In a study conducted with judo athletes, Fukuda et al. [49] investigated the impact of 4 weeks of training for the competition. The athletes were divided into two groups according to age, children (n = 8) and adolescents (n = 12). In order to improve grip strength-endurance, the participants performed at the end of the morning training session, which was performed four times a week, two sets of exercises of climbing a 9-m rope, nailed to the roof. The researchers used as a procedure to evaluate strength-endurance a 30s rope pull test in a specific equipment that recorded the pulled length in meters. No differences were found between the pre- and post-training evaluations for both children (pre: 24.7 ± 1.2 m, post: 25.7 ± 1.7 m) and adolescents group (pre: 30.0 ± 0.7 m, post: 30.6 ± 0.5 m), which shows that the exercises of climbing the rope during four weeks of pre-competitive training did not promote significant adaptations in handgrip strength-endurance in youth judo athletes.

A study carried out by Franchini et al. [45] investigated the influence of two models of resistance training periodization, linear and undulating, on some performance capabilities of judo athletes. Athletes in the adult male category were divided into two groups and underwent eight weeks of strength training following one of the two periodization models. One group followed the linear model (n = 6) and the other followed the undulating model (n = 7), simultaneously with the judo training. Isometric and dynamic strength-endurance were assessed through isometric judogi chin-up and dynamic judogi chin-up tests, both gripping a judogi rolled around the bar. For the linear training routine, the athletes performed in the first two weeks exercises with a load of 3-5 maximal repetitions (RM), from the third to the fifth week power exercises of 6-8 repetitions with a load of ~ 80% of 1RM, and from the sixth to the eighth week the objective was the development of strength-endurance, while the undulating group carried out the same training program for the sets and loads, varying the daily training and not per week as in the linear one, performing strength exercises (3-5 RM), power (6-8 RM) and strength-endurance (15-20 RM) in the same week. At the end of the eight weeks, both groups had executed the same total training load, differing only in its distribution.

The results (Table 8) show no effects of time, the training protocol and the interaction of both for the number of repetitions in the chin-up test gripping the judogi. However, there were differences in the time of suspension in the chin-up test gripping the judogi post-training in relation to the pre-training values, for both models of periodization. As a result, eight weeks of linear or undulating training induced an increase in isometric strength-endurance gripping the judogi grip, and this improvement is an important adaptation for the judogi grip during the judo match since it represents a large part of the actions during the combat. As the 1RM percentage tests were performed with the maximum load of each moment, there were no alterations in the number of repetitions in the different exercises. However, when considering the volume performed (load times the number of repetitions), there was an increase in bench press and squat for both models of load progression, without differences between them.

Table 8: Strength-endurance performances of judo athletes before and after eight weeks of linear or undulating strength training programs (Adapted from Franchini et al. [45]).

Variables	Linear (n = 6)		Undulating (n = 7)	
	Before	**After**	**Before**	**After**
Row at 70% de 1RM (rep)	21 ± 5	21 ± 4	21 ± 6	21 ± 5
Bench-press at 70% de 1RM (rep)	19 ± 3	20 ± 3	21 ± 7	22 ± 5
Squat at 70% de 1RM (rep)	23 ± 4	25 ± 3	25 ± 7	25 ± 6
Total load lift, row at 70%1RM (kg)*	1468 ± 461	1576 ± 330	1428 ± 552	1563 ± 542
Total load lift, bench-press at 70%1RM (kg)*	1266 ± 323	1479 ± 304	1397 ± 578	1590 ± 492
Total load lift, squat at 70%1RM (kg)*	1898 ± 527	2117 ± 434	1923 ± 691	2076 ± 713
Dynamic judogi chin-up (rep)	13 ± 6	14 ± 8	14 ± 8	17 ± 8
Isometric judogi chin-up (s)*	32 ± 18	41 ± 21	41 ± 14	46 ± 13

Total load lift = load multiplied by the number of repetitions; * moment effect ($P < 0.05$)

5. Methods for development of strength-endurance in striking, grappling and mixed combat sports athletes

5.1. Striking combat sports

It is up to the trainer and/or strength and conditioning professional to choose the main methods for the development of the physical qualities that are essential to differentiate winners and losers in combat sports.

The current format of the boxing matches has led to changes in the training methods, giving greater emphasis on improving the performance of the dynamic actions related to the frequency of attacks made in the first stages of the rounds, affecting the total amount during combats [50]. In fact, the ability to perform a higher number of punches on a sandbag in a pre-determined time is related to specific dynamic strength-endurance in boxing, and it is likely that strength-endurance training will improve this ability [7,8]. We still have no knowledge of studies that correlate the number of attacks made by an athlete in a combat with the sporting success in a boxing competition. However, it is possible to suggest that this improvement can be transferred to the performance of the athletes during the competition, which results in victory in the match.

Circuit training can be an effective tool for the development of dynamic strength-endurance for boxing, since there is a history in the literature mentioning that American athletes who participated in the Olympic Games in Atlanta (1996), performed circuit training for the various muscle groups, once per week, during the basic preparation period, with the aim of improving strength-endurance [51].

Based on the results of Chaabène et al. [13], which show that there is a greater sensation of fatigue in the lower-body muscles in karate athletes, it would be important to carry out a specific training for these regions, especially using motor actions characteristic of the modality and based on the temporal structure. As the match simulation results in a lower perception of fatigue in relation to the official competition, the inclusion of exercises (e.g., squats) involving strength-endurance during the break periods in the simulated match can help to improve the simulation to achieve the competition demand.

In turn, Turner et al. [52] suggest that plyometric training can also have a positive effect on endurance to maintain power actions since the efficient use of the stretch-shortening cycle results in the improvement of the propulsive force and conservation of energy. Therefore, this greater energy saving in each action would result in greater endurance throughout the repetition of these techniques.

5.2. Grappling combat sports

Grappling combat sports require high levels of dynamic and isometric strength-endurance, due to the intense nature of the actions during the combat and the short interval between actions, being recognized its importance in the sporting success and the necessity of its development during the competitive preparatory period for a competition [53].

Numerous strategies are used by coaches and strength and conditioning professionals in order to improve the performance of judo athletes concerning strength-endurance, mainly to improve the *kumi-kata* (judogi grip) during combat.

The changes in the judogi grip during judo matches are constant and correspond to a large part of the combat time, as verified by Miarka et al. [19]. Achieving and maintaining them efficiently can translate into the victory of combat [37], and the possibility of reducing the loss of performance of these actions during the matches or a competition, is a strategy that must be prioritized during preparation. Therefore, it is important that the training periodization be directed to make the judo athletes maintain their strength level during the matches, so it is important to develop the strength-endurance of the forearm flexor muscles [54].

The development of strength-endurance in a given muscle group depends on volume, and the literature indicates that multiple sets of moderate (10-15) to high (15-20 or more) number of repetitions are required, separated by rest intervals shorter than 1 min and from 1 to 2 min, respectively [55]. In addition, circuit strength training has been shown to be effective in increasing strength-endurance levels, due to the reduced rest time between exercises since it is the sufficient time to moving on to the next exercise in the circuit sequence. Regarding the frequency, the recommendation made for the advanced level athletes can be taken into consideration, being able to use a high frequency, from 4 to 6 training sessions per week with alternating muscle groups between sessions [2].

Therefore, exercises for the upper body, whose actions are to pull or to push, which are specific actions of the match, should be used in the physical preparation of judo athletes, considering the recommendations here presented. In fact, it is very common to use circuit training as a means to develop strength-endurance in judo athletes. The training sessions can be developed according to the specific demands of the modality, and therefore, considering the effort: pause ratio, it can be based solely on strength exercises or combined with conditioning exercises (i.e, sprint, shadow *uchi-komi*, etc.) [56].

Lahart and Robertson [57] mention that a specific circuit for judo athletes can last for 5 minutes, consisting of 10 exercises with a duration of 20s and intervals of 10s for the change of exercise would be performed, and the exercise could be repeated two or three times with 10-minute intervals between each set.

For wrestlers, circuit training has also been employed in order to simulate the specific demands of the match with an environment close to the demands of combat, mainly to improve strength-endurance, which is vital for successful performance, being circuit strength-endurance training a convenient and effective tool, since it physiologically prepares the athlete for the conditions that occur during the competition [2].

5.3. Mixed combat sports

Based on the analysis of the structure of the MMA combats, Del Vecchio et al. [58] suggested the use of a circuit composed of two low-intensity 15s segments, involving standing fighting actions, followed by 9s of high-intensity effort. In the sequence, the athlete would rest for 10s and perform three segments of 20s of low-intensity actions in ground fighting, followed by 15s of high-intensity actions in the ground, a new period of 10s of pause or 20s low-intensity actions on the ground. Another example presented by authors would be the execution of two blocks with the following sequence: 15s low-intensity upper-body actions; 9s of high-intensity upper-body actions; 15s of low-intensity lower-body actions; 9s of high-intensity lower-body actions; 10s of pause; three consecutive sets interspersing 3s high-intensity actions on the ground with 5s low-intensity actions. This reference can be used to create circuits with different exercises that contemplate the muscle groups that a certain athlete reports with the presentation of greater fatigue during the match.

6. Non-traditional training to improve strength-endurance for combat sports

Training that includes non-traditional exercises can be applied to improve performance and has been employed as a method of developing the required physical capabilities in combat sports, since the exercises performed in this type of training are intended for transfer to the sport, with movements similar to the motor actions involved in combat [6].

The unconventional strength training method employs the use of coordinated movements involving multiple muscle groups and joints with angles and planes of motion similar to those used in the aimed modality, which differ from the so-called conventional training method that is commonly used by bodybuilders, emphasizing the training of isolated muscle groups and in a single movement plane [6].

To improve strength-endurance in different combat sports, the training with functional movements of pushing, pulling and rotation, are those that should be used, since they are motor actions that are usually performed during combat, and strategies can be used for individual, pairs or group training, using only the body mass as loads. It is also possible to perform exercises with materials such as medicine ball, dumbbells, kettlebell, sandbag, ropes, tires, etc. (Table 9). Even so, they can be designed in circuit training, alternating functional exercises with other traditional movements used in strength training, such as squat exercise variations, among others.

The carrying out of activities follows the same recommendations in terms of the number of sets, loads, intervals and speed of execution or time-motion structure of the combat, as discussed above.

Table 9: Unconventional exercises recommended for combat sports athletes (Adapted from Santana & Fukuda [6]).

Exercise		Objective	Combat sport
Sit-up with trunk rotation holding a medicine ball		Abdominal strength-endurance	Striking; Grappling; Mixed
Pull-up	Gripping a kimono	Upper-body strength-endurance	Judo; Jiu-jitsu
	With a hook grip	Upper-body strength-endurance	Wrestling; MMA
Dragging tires	Pulling using ropes	Upper-body strength-endurance	Judo; Jiu-jitsu
	Pull with the rope tied to the body	Trunk and lower-body muscles strength-endurance	Wrestling; MMA
Push or flip tires	Supine position	Upper-body strength-endurance	Judo; Jiu-jitsu; Wrestling; MMA
	With a partner		
Car pushing		Trunk and lower-body muscles strength-endurance	Judo; Jiu-jitsu; Wrestling; MMA
Rope climbing		Trunk and upper-body muscles strength-endurance	Judo; Jiu-jitsu; Wrestling

7. Exercises for the core zone

In combat sports, the region near the center of mass is very important for the transfer of power from the lower extremities to the upper regions of the body [56]. This region has been designated as the central zone (core area or core zone), stabilization center (core stability) or power zone (power zone) and is composed mainly of the gluteus, abdomen, thigh and lumbar region muscles [59,60]. It has been considered that the strengthening of these muscle groups is important to prevent injuries, as well as to provide greater stabilization and protection of the spine and hip for the actions performed with high levels of strength or power [60]. Another important point to consider for the need to strengthen this region, refers to the need to execute (e.g., during the execution of a circular kick) and resist (e.g., during the defense of a throwing technique) the application of rotational force, and therefore, should be included in the training program for combat sports athletes [59, 61]. Indeed, international level judo athletes presented higher trunk extensor isokinetic strength and smaller trunk angular displacement after anterior trunk loading [62, 63]. Therefore, trunk extensor strength and trunk stability are discriminant variables and should be considered to improve judo athletes' performance. It is likely that these results also apply to other grappling combat sports.

McGill et al. [64] indicated that striking actions are dependent on impact and velocity. However, at the same time that some muscles act to accelerate a given body segment, the stiffness reduces the speed. Thus, in this phase the muscle relaxation can be an important factor to the action, but the for the increase in the effective mass the stiffness is important. Therefore, a double activation peak during these actions would be the best procedure to generate a higher speed, impact and power. Indeed, these authors indicated that high-level MMA athletes presented this profile for several techniques such as the back kick, the roundhouse kick, the jab with straight right combination, and for the ground and pound.

As core muscles were involved in this double peak profile, Lee and McGill [65] submitted Muay-thai athletes to six weeks of isometric core training, dynamic core training or to a control condition. The exercises included in the isometric core training were the plank, bird dog, torsional buttress (weeks 1 and 2), anterior pallof press, posterior pallof press, suitcase hold, anti-rotation pallof press (weeks 3 and 4), stir the pot, inverted row, kettlebell unilateral rack walk, half kneeling woodchop (weeks 5 and 6). During weeks 1, and 3 to 6, training sessions were executed four times per week, whereas in week 2 they were executed 7 times per week. Five to ten 10s sets were executed. The dynamic core training group executed the curl up, superman, side curl up, twisting curl up (weeks 1 and 2), advanced curl up, back extension, Russian barbell twist (weeks 3 and 4), curl up twitch, superman twitch, lateral medicine ball throw, and rotational medicine ball throw (weeks 5 and 6). Frequency was the same as for the isometric core group. Five sets of 5 to 10 repetitions were executed. Athletes executed the jab, cross, jab and cross combination, knee technique pre- and post-training and analyzed peak force, peak velocity and EMG of several core muscles. They reported that the isometric core training resulted in higher impact force, whereas the dynamic core training resulted in higher speed during the techniques after the six weeks of training. EMG of core muscles increased after both training types, and there was a change from a one-peak pattern pre-training to a double-peak pattern post-training. Therefore, strength-endurance core training can improve impact force and velocity of striking techniques, but the changes vary between isometric and dynamic training approaches. These results suggest that coaches and strength and conditioning professionals should choose one of the approaches to induce specific change accordingly to their athletes' needs.

8. Final considerations

Strength-endurance is an important aspect for the success of combat sports, varying in terms of the most relevant muscle groups to be developed in grappling and striking combat sports. Therefore, the analysis of the requirements of the specific modality, as well as the individual needs of the athlete, and the evaluation of the initial condition of the athlete should be the starting point for conducting the development of strength-endurance. The specific procedures and exercise suggestions presented in this chapter are some recommendations for professionals, but innovation and the conduct of the process based on scientific evidence should be considered for the continuous improvement of this important performance component.

Conflict of interest

None declare.

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CHAPTER 6
Developing flexibility for combat sports athletes

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Abstract
The range of motion of a joint is extremely important in combat sports, especially when there is a need to execute a certain motor gesture with maximum range of movement, as in throwing techniques such as *uchi-mata* in judo, certain types of guards in Brazilian jiu-jitsu or the high kicks common in a variety of striking combat sports. Therefore, in this chapter, we will discuss the elements related to flexibility response during training sessions or combat sports competitions, flexibility tests commonly used for these athletes, and the monitoring and control of the evolution of flexibility in athletes. We will also present the means and methods used for the development of flexibility and longitudinal studies on the development of flexibility in combat sports athletes. Finally, this chapter supports based on the evidence the inclusion of flexibility development within training sessions is an important consideration to maximize performance and other physical capabilities that may be affected both acutely or in the long-term by flexibility.

Keywords: Martial arts; combat sports; flexibility; range of motion; stretching.

1. Introduction

Flexibility is defined as the range of motion in a joint or a group of joints [1]. A good level of flexibility, in addition to the execution of movements, helps to prevent injury [2-4]. The range of motion of a joint is extremely important in combat sports, especially when there is a need to execute a certain motor gesture with maximum range of movement [5], as in throwing techniques such as *uchi-mata* in judo [6], certain types of guards in Brazilian jiu-jitsu [7] or the high kicks common in a variety of striking combat sports [5].

In fact, in striking combat sports, such as karate, studies have shown greater flexibility in combat sports athletes compared to physically active controls [8]. One study conducted with children showed that six months of karate practice resulted in improved flexibility that was more pronounced than when practicing team sports [9]. In addition, the introduction of dynamic stretching exercises, used as a means of warming up in Olympic wrestling training sessions, have been shown to improve various physical capacities (e.g., maximum strength, muscle power, and muscular resistance) compared to warming up without stretching exercises [10]. On the other hand, there are reports that indicate that long-duration static stretching before strength and muscle power sessions can be counterproductive from an acute point of view [11-13]. Longitudinal studies, however, note greater performance in activities involving maximum strength and torque [12]. This conflict between the long-term benefits and the short-term performance decreases that could occur led the European College of Sport Science to label stretching exercises a paradox [2] and recommend isolated sessions for the development of flexibility.

In this sense, a recent review [14] concluded that there is strong evidence suggesting that static stretching causes only trivial negative effects on subsequent strength and power performances if the accumulated duration per muscle group does not exceed 60 s. The authors state that static

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stretching is an important warm-up component in recreational sports duet to its potentially long-term positive effect on flexibility and musculotendinous injury prevention but in high-performance athletes, minimum performance differences can have a major impact on athletes' success in competition, and such intervention should be avoided before competition.

Furthermore, there are no detailed studies comparing flexibility in different joints between elite athletes and non-elite practitioners in sports such as karate, although, considering the type of techniques prevailing in international competitions, reaching extreme values in the range of motion is probably unnecessary for athletes [5,15]. Something similar may occur in other sports, since high kicks - requiring great flexibility - are not among the most frequently used techniques in striking combat sports [16,17] and, in the example of kickboxing, do not represent a difference in receiving a medal or not [18]. On the other hand, limited flexibility could be a serious disadvantage among mixed martial arts fighters, a sport in which practitioners stretch their range of motion to an extreme [19].

An important and not yet explored aspect of the evaluation of flexibility in combat sports is dynamic flexibility, which consists of performing fast or slow movement of the joint as a result of the contraction of the antagonist muscles throughout the range of motion [20] and which is arguably more important in such sports, versus static flexibility, mean slowly applied a passive movement of a muscle to the maximum range of motion, followed by maintenance of the position for a long period [20] and is the type most commonly measured in athletes [5]. In fact, studies conducted in combat sports such as Brazilian jiu-jitsu [21], judo [22], Olympic wrestling [23], karate [5], mixed martial arts [24] and taekwondo [25] have used the sit and reach test — a static test — for its ease of application. However, the use of these tests among combat sports athletes has been questioned [5,25]. In addition, results obtained have been contradictory. Recent reviews [25] report that athletes have high values of flexibility (that is, above the 80th percentile for males and between the 70th and 100th percentile for female), whereas other studies have found values close to the average for the general or physically active population [26]. In addition, the wide range in the results is likely due to different equipment and evaluation methodologies, for example some equipment may present an advantage of 26 cm [27]. Taekwondo coaches consider flexibility as a variable of medium importance for the performance of the sport [28]. Judo coaches classify flexibility as less important, positioning this attribute after speed, sport-specific resistance, and variables associated with strength training, coordination and balance [29]. Although Yoon [23] indicated in his review that the best-ranked Olympic freestyle wrestlers had greater flexibility than lower-ranked athletes, higher-level athletes are more flexible than lower-level athletes [30]. A case study with a four-time world champion demonstrated lower values in trunk and shoulder flexibility compared to national standards, yet higher values on the sit and reach test [31]. In fact, Yoon [23] mentions that there may be an adaptation in terms of flexibility, since there are indicators of greater rotation and adduction/abduction of the shoulder and flexibility in the neck region among Olympic wrestlers compared to non-athletes, but less flexibility in the wrist, suggesting adjustments or the selection of wrestlers with specific flexibility combinations. Thus, there is controversy about the influence of flexibility on performance in different combat sports.

Another important aspect to consider is that there are no specific tests to evaluate the flexibility of combat sports athletes or recommended protocols to follow.

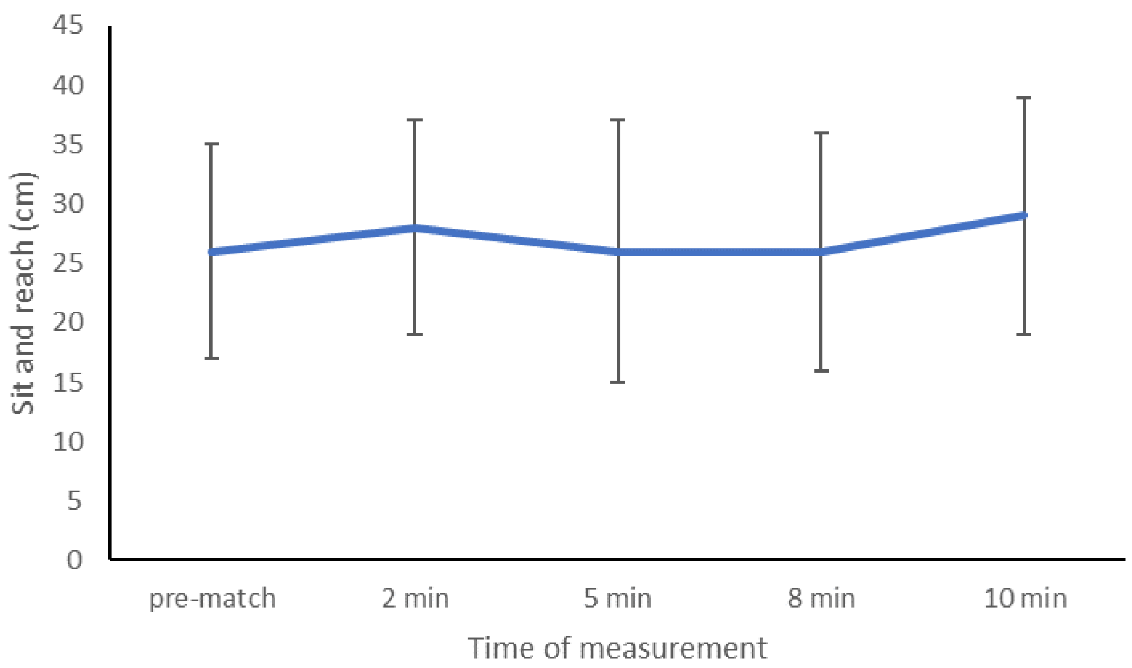
Therefore, in this chapter, we will discuss the elements related to flexibility response during training sessions or combat sports competitions, flexibility tests commonly used for these athletes, and the monitoring and control of the evolution of flexibility in athletes. We will also present the means and methods used for the development of flexibility and longitudinal studies on the development of flexibility in combat sports athletes.

2. Flexibility response in different combat sports during training sessions or competitive matches

Some papers have attempted to verify the contribution of flexibility for the execution of certain taekwondo kicking techniques [32,33]. Yu et al. [33] concluded that the stature and flexibility of an athlete were related to the height of the *neryo-chagi* kick. In the study, the authors analyzed 3D film recordings of advanced taekwondo athletes (n = 8, with an average of 5 years of experience in the sport) and professionals (n = 4; with an average of fifteen years of experience). The two groups were compared using a 14-segment model to determine the relative contribution of the flexibility of different joints to kick performance. The technique was divided into four phases: decoy (preparation), power load (main phase of the technique), drive (descending phase of the technique), and landing and stabilization. During the power load phase, the range of motion was greater for professional athletes, reaching 206.1 ± 9.1º for the hip and 99.6 ± 6.7º for the knee, respectively, whereas the equivalent figures for the advanced group were 183.6 ± 8.9º and 27.4 ± 8.3°, respectively. Although professionals had higher values, the time spent at this stage (power load) was significantly shorter (0.06s, 17% faster) than the time taken by athletes in the other group. For the drive phase, professionals also generated a greater range of motion in the hip (139.1 ± 6.2 °) compared to advanced athletes (122.4 ± 5.7 °), with a movement that was 0.04s faster. Results indicate that flexibility contributes to technical effectiveness.

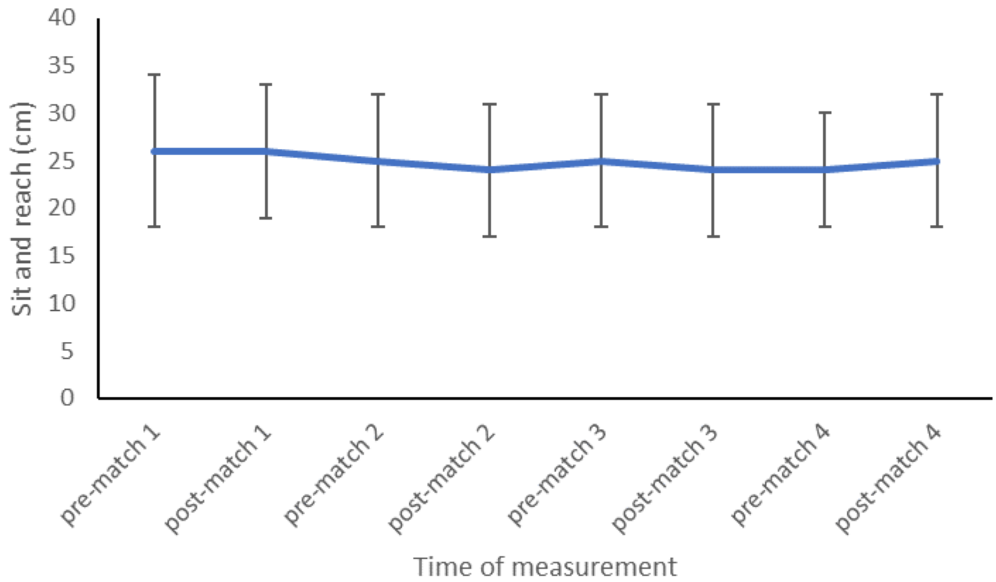
Professional athletes use a greater range of motion to generate a higher kick, which would be difficult for athletes with low levels of flexibility. In addition, the extreme angle between the two thighs at the end of the power load phase provides the initial conditions necessary to increase the length of the hip flexors before contraction. According to the authors, this dynamic pre-stretch results in greater muscle strength, based on the relationship between length and muscle tension, which increases kick effectiveness. In fact, the athletes had a higher maximum height during the execution of the kick. Finally, the researchers suggest that hip flexibility, muscle power (not addressed in this chapter) and the whip-type movement of the leg that kicks are key factors in the quality of the technique. The combined effect of these factors can explain the 15% difference in action time, the 12% difference in kick height and the 20% difference in maximum speed between professionals and advanced athletes. A study by Wasik and Chan [32] complement the work Yu and colleagues [33]. These authors indicate that during the rise of the leg in preparation for the kick, the slight flexion of the trunk in the direction of the leg executing the kick is responsible for increasing the range of motion of the hip joint, emphasizing that this increase would generate a pre-stretching of the extensor muscles of the hip and contribute to a higher final kick height.

We found only one study that analyzed the variation of flexibility during a match [34] and another the investigated this variation during the jiu-jitsu simulated competition [35]. No difference was found when the results of the sit and reach test considered different durations of a simulated match (Figure 1) [34] or during the four simulated matches (Figure 2) [35], indicating that flexibility remains stable both during the match and throughout the competition.



Values are mean ± standard deviation.

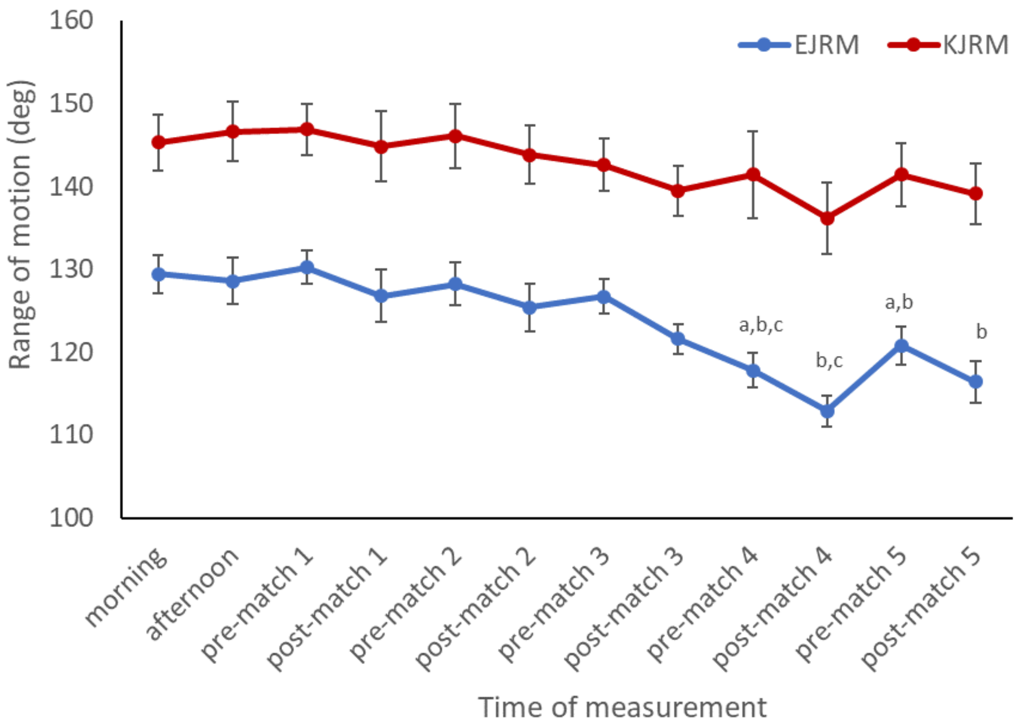
Figure 1: Sit and reach test performance, before and after jiu-jitsu different duration matches (Adapted from Andreato [34]).



Values are mean ± standard deviation.

Figure 2: Sit and reach test performance, before and after four simulated jiu-jitsu matches (Adapted from Andreato [35]).

Although the objective of the study was to evaluate flexibility, Barbas et al [36] analyzed the effect of successive matches on the range of motion of the knee and elbow joints. More specifically, knee and elbow movements were used as an index of muscular edema resulting from match performance, using the angle in which the athletes reported discomfort as the reference to determine the maximum range of pain-free movement. Although the authors did not report flexibility measures to verify how this capacity would be associated with the response, differences may help to understand how performance in a simulated competition may restrict the flexibility of athletes. Figure 3 shows the main results observed in this study.



a = different from the base condition ($p < 0.05$); b = different from match 1 ($p < 0.05$); c = different from previous match ($p < 0.05$).

Figure 3: Range of motion measurements of elbow (EJRM) and knee movements (KJRM) of Olympic Greco-Roman wrestling during baseline measurement (morning and afternoon) and simulated competitions (Adapted from Barbas et al. [36]).

As shown in Figure 3, only the range of motion of the elbow joint decreased during the simulated competition. According to the authors, this response is due to an increase in the blood creatine kinase concentration, which results from micro-ruptures of muscle tissue. Thus, the pressure and edema around broken tissues generate muscle pain, loss of strength and a decrease in the range of motion, which could negatively affect the technical performance of athletes, due to the compensatory movements made in an attempt to protect the injured tissues. The decrease in range of motion in the upper limbs may be the result of a more pronounced request in this region during the matches.

In turn, Dezan et al. [37] reported that during Olympic wrestling matches it is common for athletes to perform fast trunk flexion movements, resulting in a front pelvic tilt, which requires high flexibility of the hamstring muscles. This type of movement is also present in other combat sports and in the practice of mixed martial arts, indicating that athletes should improve the flexibility of this muscle group.

3. Flexibility tests commonly used for combat sports athletes

Sterkowicz and Franchini [38] suggested testing the flexibility of karate athletes using the *mawashi-geri* technique. The athlete attempts to achieve the highest possible height over five repetitions, which would be considered in relationship to the height of the performer by means of the following equation:

Index = maximum amplitude of kick / height of the athlete.

Table 1 presents the classification indicated by the authors for the different results of amplitude.

Table 1: Classification of flexibility results of the mawashi-geri kick (Adapted from Sterkowicz and Franchini [38])

Index result	Classification
< 0.97	Very low
0.98 a 1.05	Low
1.06 a 1.07	Regular
1.08 a 1.14	Good
> 1.15	Excellent

According to the authors, the athletes with the highest level of technical competence had the highest flexibility values measured using this test, in comparison to lower-level athletes (fourth and third *kyu*). However, no difference was observed in the index between athletes of different weight categories (-70 kg = 1.1 ± 0.07; -80 kg = 1.1 ± 0.05; +80 kg = 1.1 ± 0.05).

As sports training can generate negative adjustments due to the high volume and intensity of training, it has been suggested that the monitoring of imbalances in contralateral and ipsilateral segments may be important due to the increase in the probability of injury occurrence [8]. In this sense, measurement - by means of goniometry - of the flexibility of specific segments, such as flexion and extension of the knee and hip, medial and lateral rotation of the hip, flexion and dorsiflexion plantar, and inversion and eversion of the foot has been recommended for karate athletes [8] and could be extended to other combat-sports athletes who frequently use kicks as part of their sport.

Undoubtedly, the most frequently used test to evaluate flexibility is the sit and reach test [39], which is also frequently used for combat-sport athletes [26]. Schwartz et al. [26] evaluated many combat-sport athletes and reported mean values for all groups compared to the values established by the American College of Sports Medicine: Brazilian jujitsu (n = 136) = 27.3 ± 9.1 cm; judo (n = 180) = 29.0 ± 8.4 cm; karate (n = 229) = 30.3 ± 8.0 cm; kung fu (n = 140) = 31.5 ± 8.6 cm; taekwondo (n = 250) = 30.2 ± 9.0 cm. The authors reported that the average classification in the striking combat sports are due to the fact that movements that require high levels of flexibility are not common in training situations. For example, kicking techniques are performed at the level of the chest and not at head height.

Among judo athletes, values between 28.0 ± 6.3 cm have been observed in Belgian athletes in the lighter categories (<71 kg at the time of the study) [40] to 72.98 ± 11.21 cm in Croatian youth athletes [41]. In a study conducted in 36 judo athletes between 10 and 13 years of age [42], it was noted that flexibility - measured by the sit and reach test – was higher in children who practiced the morote-seoi-nage technique in relation to a control group who did not practice any technique. Therefore, the inclusion of the sit and reach test has been recommended as part of the evaluation of athletes who practice techniques that include hip flexion [43]. The results of one study with a large number of subjects (n= 729) is presented in Figure 4 [44]. High values are noted for all, with the exception when compared with Croatian athletes. It is important to note that the flexibility test results shown in Figure 4 do not differ between categories [44], indicating that flexibility seems to have the same degree of importance in all categories.

On the other hand, Toskovic et al. [45] did not observe any difference in performance on the sit and reach test between beginner and experienced taekwondo athletes. The more experienced taekwondo athletes, however, outperformed the other group in the lateral split leg test, a result that was attributed to the greater specificity of the test. For judo, Taylor and Brassard [46] found no significant correlation between the performance in the sit and reach test and skill level of athletes.

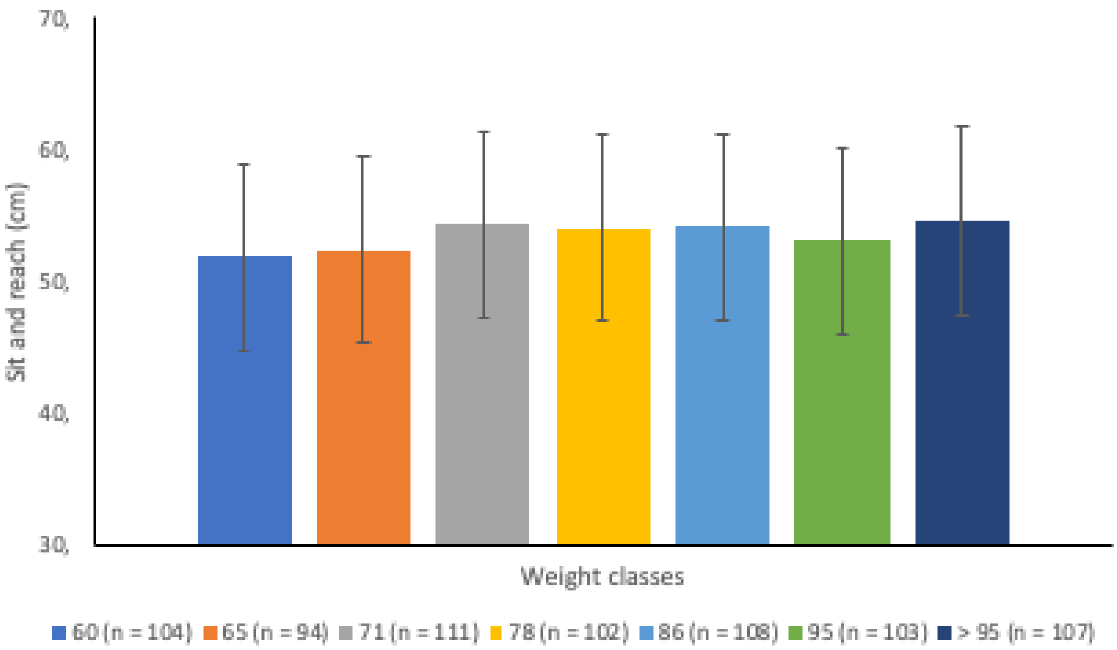


Figure 4: Performance in the sit and reach test among Japanese university judo athletes of different weight categories (in kg) (Adapted from Iida et al [44]).

Therefore, the development of specific flexibility tests may be necessary to improve the evaluation of combat-sport athletes.

4. Longitudinal studies on flexibility development in combat-sport athletes

There are few published studies on the effect of different types or phases of training on the flexibility of combat sports athletes [47].

Herman and Smith [10] reported that among Olympic freestyle wrestlers, the inclusion of dynamic stretching movements during the warm-up phase of a four-week program affected a number of variables when compared with a warm-up without stretching. More precisely, the authors reported increases in: peak torque in the extension of both knees, standing long jump distance, medicine ball throw distance, the number of abdominal repetitions, and the number of push-up repetitions. They also noted decreases in 600m running time and time to complete an agility test. It is important to highlight that in this study both groups had the same training program, with the only difference being the dynamic stretching exercises included in the warm-up before each specific session training for the experimental group.

Mirzaei et al. [31] found that four weeks of training in the general preparation phase, was sufficient to increase flexibility, as measured by the sit and reach test, in young Olympic freestyle wrestlers, from 33.00 ± 5.35 cm to 34.66 ± 5.91 cm. Conversely, Crnogorac et al. [48] found that three weeks of training during the general preparation phase resulted in decreased flexibility of the shoulder (from 69.00 to 67.15 cm) and lower values on the sit and reach test (from 39.22 cm to 37.77 cm) among female judo athletes. The authors did not offer explanations for this decrease in flexibility performance, however, it is possible that with the exception of the specific judo sessions, in which some kind of flexibility practice may have been incorporated, there is no description of this type of exercise in other training sessions, such as strength and power training, aerobic and anaerobic conditioning.

In an analysis of a four-week judo training program in preparation for a national level competition, Fukuda et al. [49] observed increases in flexibility, measured through the sit and reach test, in a group of children (9.9 ± 1.6 years; pre = 26.4 ± 4.3 cm; post = 29.4 ± 3.5 cm), but not in the adolescent group (15.3 ± 2.0 years, pre = 34.1 ± 6.9 cm, post = 35.3 ± 7.7 cm). The lack of change in the adolescent group may be explained by the fact that pre-training values were already reasonably high among adolescents compared to children. However, the authors stated that the focus of training (learn to train in the case of children, and train to train in the case of adolescents) could better explain the different results observed in the study.

For striking combat sports training (e.g., taekwondo), it has been observed that 12 weeks of low-frequency training (twice a week for 50 minutes each day, plus two weekly school physical education classes of 50 minutes each) was enough to improve flexibility, measured through the sit and reach test, among female adolescents (16.2 ± 7.0 cm before intervention and 18.2 ± 6.4 cm after the intervention). No change was observed in the control group exposed to physical school education only (15.9 ± 8.8 cm before the intervention and 15.6 ± 7.0 cm after the intervention) [50]. These results are consistent with the hypothesis of the researchers and can be attributed to the fact that taekwondo training involves multiple series of static and ballistic stretching, which was adequate to improve flexibility [39].

A common concern among combat sports coaches and athletes is how increased strength training may limit the range of motion. In fact, this concern seems to have originated in the fact that high levels of muscle development could limit flexibility by mechanical blockage, that is, muscle volume would be a barrier to the maximum range of motion. However, at present, it is known that strength training does not appear to adversely interfere with flexibility and may even improve it, especially when load weight-bearing exercises are performed with a high range of motion [39] and when resistance exercises are executed in order to prevent hypertrophy, which would result in a change in the weight category [47]. However, there are few studies on the influence of strength training on flexibility in combat sports athletes.

Recently, researchers [51] studied the effect of strength training and the order of exercises on flexibility among judo athletes and found that the use of a sequence of exercises for the upper-body, followed by exercises for the lower-body resulted in a difference in flexibility compared to the reverse order. However, for the groups subjected to each order of exercises, there was an increase in the flexibility in flexion, extension, adduction and abduction of the shoulder, and flexion and extension of the trunk and hip. Thus, typical resistance exercises can be used to increase the flexibility of judo athletes when completed with the full range of motion for each exercise.

Additionally, a pilot study developed with young judoka [52], applied 5 weeks of suspension-training. The suspension-training program was applied three times per week. All suspension-training sessions begun with a 5-7 minutes period of continuous low-intensity jogging warm-up. Then athletes perform two sets of 30 seconds of static stretching exercises using the suspension gear. The stretching drills were repeated at the end of each suspension-training sessions. The difficulty of the drills and the volume was progressively increased during the 5 weeks of training. A typical suspension-training session last ~ 20 minutes. The results indicated a significant improvement in the seat and reach test after the training program (42.1 ± 8.2 vs 46.2 ± 7.5). The authors propose that the eccentric activation of most of the exercises could have induced sarcomerogenesis, increasing muscle length and therefore flexibility. However, it is important to note that the study only had an experimental group, with a total of ten participants, and without the participation of a control group.

5. Means and methods to develop flexibility in combat sports athletes

Although there are no clear recommendations on the ideal frequency, intensity, and duration of a program to improve flexibility, some indications have been reported to guide program development aimed at improving this capacity [39].

Shellock and Prentice [53] cite four types of frequently used techniques to increase flexibility: static, ballistic, dynamic and proprioceptive neuromuscular facilitation. Hume and Reid [20] define each of these techniques, with advantages and disadvantages as follows:

a) *Static*: a passive movement of a muscle to the maximum range of motion, followed by maintenance of the position for a long period. The main advantages are the increases in the range of motion and the simplicity of the technique. The disadvantages include the reduction of muscular strength after this type of work and the possibility of injuries. The utilization of this technique consists of performing exercises with the help of another person or an apparatus, resulting in the same advantages and disadvantages with the additional difficulty of determining the external force generated by the other person or by the apparatus.

b) *Ballistic*: repetitive ballistic movements at the edge of the range of motion of the stimulated joint. The advantage includes the sharp increase in range of motion, but may increase the likelihood of strength reduction in the exercise performed immediately after the flexibility exercise. In addition, there may be an increased risk of injury.

c) *Dynamic*: fast or slow movement of the joint as a result of the contraction of the antagonist muscles throughout the range of motion. The advantages and disadvantages of this method are unknown.

d) *Proprioceptive neuromuscular facilitation:* involves the activation and reflex inhibition of agonist and antagonist muscles. The advantage is associated with an acute increase in the range of motion, with the disadvantage of a decrease in muscle power immediately after these exercises. This method has an additional disadvantage depending on the experience of the person to regulate the combination of stimuli to the agonist and antagonist muscles.

During static exercises there are resting and stretching of the elongated muscles, slowly and gradually, avoiding the occurrence of the stretching-reflex. For this technique, the recommendation is that this exercise is maintained for 15 to 30 seconds, although the upper limit of this range should be maintained with moderate discomfort, but without feeling pain [39]. Moreover, Hume and Reid [20] reported no significant differences between 30 and 60s exercises. In addition, the authors affirm that the work of a single set is as effective as three sets. It has also been recommended that flexibility exercises be carried out after the completion of the warm-up, as this procedure helps in obtaining a greater range of motion during the flexibility session [39].

With respect to time to improve flexibility, it takes four to six weeks to make significant changes, while a four-week interruption in flexibility training results in a return to pre-training values [20]. Regarding the detrimental effects of static stretching, Blazevich et al. [54] studied the acute response of static stretching of short duration (5 s) and moderate (3 x 10 s), without finding a harmful effect in the tests of sprinting, jumping and change of direction. Therefore, the inclusion of short-duration static stretching is unlikely to affect the performance in these variables when performed as part of a comprehensive warm-up routine. Additionally, a recent review concluded that static stretching less than 60 s only has a trivial effect on strength and power performance [14]. Thus, it could be an appropriate method to use within the warm-up in recreational athletes, but it must be used with caution in high-level athletes, because small losses of strength and power could make the difference between winning and losing at this level. Additionally, in jiu-jitsu athletes the practice of three static stretching exercises with three sets of 20 s each, with a total of 180 s stretching, produced a decrease in maximal strength (1-RM) in the bench-press [11]. Therefore, high level combat sports athletes should avoid static stretching during competitions and sessions aimed at developing maximal strength and muscle power.

In the case of dynamic techniques, specific movements from each sport have been used [20]. Essentially, this type of technique can be seen as the active movement within the range of motion of the joint required in the sport [39]. Thus, when an athlete performs a kicking technique or a maximum range of motion *uchi-mata*, they are performing a dynamic technique to increase flexibility. This technique, to reproduce movements of the sport itself, has been widely used in the warm-up phase [10]. The main difference in the dynamic compared with ballistic techniques refers to the lack of insistence on the final stage of the first technique. In the dynamic technique, the muscle does not relax during the execution of the movement and remains active throughout the range of motion [39].

For the development of a program that involves the dynamic technique, it is important to carefully analyze the main movement patterns involved in a given sport and the required range of motion [39]. For example, for sports that involve kicks, trainings would include kicking techniques typically used by each of the athletes, becoming a specific training to the needs of each fighter. It has been recommended that the initial movements be performed with movements slightly lower than those usually executed, with progression as the repetitions increase. It is also important that the movements used are respected in terms of their structure, in order not to compromise technique [39].

The ballistic technique has been considered less beneficial than the other techniques, since it can increase the risk of injuries as a result of the reflex reaction of type Ia motor neurons and the additional resistance imposed on the muscle by cyclic and repetitive changes in length, although the evidence regarding this possibility is not available [20]. This type of technique involves active movement and the application of insistence in the final phase of the movement, without maintaining the maximum range of motion with central feature [39]. However, given the constraints previously identified [20], this technique is hardly used in programs to improve the flexibility of athletes [39].

The proprioceptive neuromuscular facilitation technique is considered more complex because it includes activation and inhibition. Frequently, in this technique, the athlete is asked to passively move a certain limb until the maximum range of motion is reached, then the muscle group is contracted in order for the muscle to be elongated for 3 to 6s. This process is followed by a rest period during which the muscle is elongated [20]. Three variations of this technique are usually employed [20,39]:

a) *Contraction-relaxation:* this technique begins with a passive pre-stretch that is maintained at a point of moderate discomfort for 10s. The athlete then performs a concentric action throughout the range of motion. Then, immediately following, the athlete relaxes the muscle involved in the action and a separate person helps with passive stretching for 30s. It is expected that autogenic inhibition will occur (i.e., activation of the elongated muscles);

b) *Maintenance-relaxation:* this technique also begins with a passive pre-stretch that is maintained at a point of moderate discomfort. Then the partner tries to move the elongated limb while the athlete prevents movement through the contraction of the muscle. This isometric action is maintained for around 6s. Next, this muscle relaxes and a passive stretch is maintained for 30s. This final stretch should be of greater magnitude due to the autogenic inhibition (i.e., activation of muscle elongating); and

c) *Maintenance-relaxation with agonist contraction:* this technique is identical to the maintenance-relaxation technique in the two primary phases. During the third phase, a concentric action of the agonist is used in addition to passive stretching. That is, after the isometric phase, the athlete directs the joint involved in stretching to a new range of motion. In this situation, the final stretch should be greater as a result of the reciprocal inhibition (i.e., activation of the agonist muscles) and the autogenic inhibition (i.e., activation of the antagonist muscles - which were elongated).

In addition, it is important to consider that with these techniques it is possible to increase strength since there is a contraction phase. Also, the presence of an additional person is required to help [20].

The recommended exercises refer mainly to the muscle groups that are used in the primary techniques of the sport, as well as exercises for muscle groups, such as the quadriceps, hamstrings, pectoralis major and latissimus dorsi.

6. Final considerations

Flexibility is an important variable to consider in the training of combat sports athletes, as various actions taken during matches are performed with a high range of motion. Based on the evidence discussed in this chapter we can mention the following points: (a) The practice of static stretching exercises greater than 60 s has been associated with a decrease in short-term maximal strength and muscle power performance [14]. Even the practice of static stretching exercises consisting of three stretching exercises with three sets of 20 s each, with a total of 180 s of stretch, produced a decrease in maximal strength (1-RM) in the bench-press in jiu-jitsu athletes [11]. Therefore, high level athletes should avoid static stretching before sessions aimed at developing strength and muscle power and during competitions; (b) Four weeks of dynamic flexibility training during the wrestler's warm-up has resulted in improvements in muscle strength, anaerobic capacity and agility [10]. Therefore, combat sports athletes should incorporate dynamic flexibility training as a supplement to strength and conditioning training; c) In recreational subjects, taekwondo practice improved flexibility due to static stretching training added to the movements of the modality, for example kicks (ballistic training) [50]. Therefore, subjects who practice combat sports recreationally, can see their flexibility improved simply with the specific practice of taekwondo-specific tasks and likely combat sports in general; d) In judo athletes, resistance training increased flexibility [52]. Therefore, we recommend strength training with concentric - isometric - eccentric activation as a complement to flexibility training.

Conflict of interest

None declare.

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