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ORIGINAL ARTICLE

Energy demands in taekwondo athletes during combat simulation

Fábio Angioluci Diniz Campos · Rômulo Bertuzzi · Antonio Carlos Dourado · Victor Gustavo Ferreira Santos · Emerson Franchini

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Abstract The purpose of this study was to investigate energy system contributions and energy costs in combat situations. The sample consisted of 10 male taekwondo athletes (age: 21 ± 6 years old; height: 176.2 ± 5.3 cm; body mass: 67.2 ± 8.9 kg) who compete at the national or international level. To estimate the energy contributions, and total energy cost of the fights, athletes performed a simulated competition consisting of three 2 min rounds with a 1 min recovery between each round. The combats were filmed to quantify the actual time spent fighting in each round. The contribution of the aerobic (W_{AER}), anaerobic alactic (W_{PCR}), and anaerobic lactic ($W_{[La^-]}$) energy systems was estimated through the measurement of oxygen consumption during the activity, the fast component of excess post-exercise oxygen consumption, and the change in blood lactate concentration in each round, respectively. The mean ratio of high intensity actions to moments of low intensity (steps and pauses) was ~1:7. The W_{AER}, W_{PCR} and ($W_{[La^-]}$) system contributions were estimated as 120 ± 22 kJ (66 ± 6%), 54 ± 21 kJ (30 ± 6%), 8.5 kJ (4 ± 2%), respectively. Thus, training sessions should be directed mainly to the improvement of the anaerobic alactic system (responsible by the high-intensity actions), and of the aerobic system (responsible by the recovery process between high-intensity actions).

Keywords Oxygen consumption · Blood lactate · Energy systems · Heart rate

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F. A. D. Campos · E. Franchini (✉)
Martial Arts and Combat Sports Research Group,
School of Physical Education and Sport, University of São Paulo (USP), Av. Prof. Mello de Moraes, 65, Butantã, São Paulo,
SP 05508-900, Brazil
e-mail: emersonfranchini@hotmail.com

R. Bertuzzi
Research Group in Endurance Performance,
School of Physical Education and Sport,
University of São Paulo, São Paulo, Brazil

A. C. Dourado
Center of Physical Education and Sport,
State University of Londrina, Londrina, Brazil

V. G. F. Santos
Sports Science Research Group,
Federal University of Alagoas, Maceio, Brazil

Introduction

Even though taekwondo is an Olympic sport, the physiological changes that occur during taekwondo combat have not yet been established. Previous studies have reported physiological profiles for male taekwondo athletes during training (Bridge et al. 2007), simulated competition (Bouhlel et al. 2006; Butios and Tasika 2007; Pilz-Burstein et al. 2010) and real competition (Bridge et al. 2009; Chiodo et al. 2011a) through the measurement of heart rate, hormonal response and blood lactate concentration. Reported heart rate values for simulated combat vary from 148 ± 2 bpm (Butios and Tasika 2007) to 197 ± 2 (Bouhlel et al. 2006), while less variation has been observed during competition, i.e., from 176 ± 10 bpm (Chiodo et al. 2011a) to 187 ± 8 bpm (Bridge et al. 2009). Greater variability in blood lactate after the match is also observed during combat simulation, i.e., from 2.9 ± 2.1 mmol L^{-1} (Butios and Tasika 2007) to 10.2 ± 1.2 mmol L^{-1} (Bouhlel et al. 2006), while values from 7.0 ± 2.6 mmol L^{-1} (Chiodo et al. 2011a) to 11.9 ± 2.1 mmol L^{-1} (Bridge et al. 2009) have been reported during real competitions. Thus, although combat simulations seem to result in lower physiological strain this is not true in all the studies and more research is needed to clarify this point. In addition, simultaneous measures of all three systems of energy transfer were not carried out in these studies, even though it has been suggested that this type of analysis is important (Markovic et al. 2008).

Estimates of energy system contributions have been performed in other combat sport, such as karate (Beneke et al. 2004; Doria et al. 2009), and muay thai (Crisafulli et al. 2009). In karate, Beneke et al. (2004) analyzed the contributions of different energy systems during the *kumite* (combat simulation). They based their analysis on the assumptions described by Di Prampero and Ferretti (1999). These authors found that the aerobic system participated more than did the anaerobic lactic and alactic systems. Similar results were found by Doria et al. (2009). In analyzing muay thai, Crisafulli et al. (2009) reported an elevated contribution from both the aerobic and anaerobic systems during a simulated match. In particular, an elevated anaerobic demand was observed at the beginning of the activity, followed by a growing aerobic contribution throughout combat. However, no studies to date have analyzed the contributions by the different energy systems (oxidative, glycolytic and ATP-CP) in combat or combat simulation in taekwondo athletes. It is believed that a good understanding of the contributions from different energetic systems during combat is relevant to the organization of training, making it more specific to the demands of the combat (Bridge et al. 2009). Therefore, the purpose of this study was to verify the physiological responses (oxygen consumption, blood lactate concentration and heart rate analysis) and estimate the contributions of the three energy systems (anaerobic alactic, anaerobic lactic and aerobic) in the simulated taekwondo combat. Our hypothesis was that, during taekwondo combat, the aerobic system would predominate when combat is considered as a whole, given that there are longer periods of inactivity and lower intensity between offensive and defensive periods, but there is moderate contribution of the anaerobic alactic system (due to offensive techniques), and a small glycolytic contribution.

Methods

Subjects

The sample comprises 10 adult male taekwondo athletes (age: 21 ± 6 years old, body mass: 67.2 ± 8.9 kg; height: 176.2 ± 5.3 cm), black belt holders, with a minimum of 5 years' experience. All of the subjects were active competitive athletes and were participating in national and international championships. These athletes were at the competitive phase of their periodization and engaged in 18–24 h of training per week, with about 15 h dedicated to technique and tactical workouts and the remaining time dedicated to strength and flexibility training sessions. To ensure that the sample was representative of high-level taekwondo athletes, males from all Olympic weight divisions were included: <58 kg ($n = 3$), 58–68 kg ($n = 5$), 68–80 kg ($n = 1$) and >80 kg ($n = 1$). Before the tests, the athletes and the parents of two underage (17-year old) athletes were informed of the procedures, including the possible risks involved, and signed an informed consent form. The oldest athlete who took part in this study was 33-year old. All the procedures had been previously approved by the local Ethics Committee.

Procedures

The athletes were grouped according to their weight class, and they engaged in simulated combat. In accordance with WTF rules, the combat lasted three rounds of 2 min each, with an interval of 1 min between, and combat took place within an official area (8 × 8 m). Although the new taekwondo rules establish the use of electronic body protectors to protect the trunk of the athlete and at the same time allow more reliable and accurate score identification (Vecchio et al. 2011), we did not use this system because it would interfere with the gas analyzer. The gas analyzer was placed on the back of the athlete and no attack to this area was allowed. Each athlete competed in one match, and only one athlete was evaluated per match. These procedures were similar to those used in studies analyzing karate (Beneke et al. 2004) and muay-thai (Crisafulli et al. 2009). During the simulated match, the following measurements were taken: heart rate, blood lactate concentration and oxygen consumption (VO_2). A video camera (Sony Vegas Pro 8.0®) was used to record the event for subsequent analysis (i.e., to quantify the amount of time spend fighting during the match). A Suunto heart rate monitor (Suunto Team Pod, Suunto Oy, Finland) was programmed to record each heart beat. The mean heart rate (HR_{MEAN}) was calculated as the average of the heart rate during the entire round, while peak heart rate (HR_{PEAK}) was defined as the highest value during each round. As previously stated (Bridge et al. 2009), the maximum heart rate determined from laboratory-based treadmill tests was lower than that obtained during taekwondo competition. Thus, we used a new approach to this combat sport (Capranica et al. 2011; Chiodo et al. 2011b), which involved the description of five categories of intensity of efforts to indicate the physical load imposed on athletes during their match simulations: (1) >95% HR_{PEAK}, (2) 90–94% HR_{PEAK}, (3) 85–89% HR_{PEAK}, (4) 80–84% HR_{PEAK}, and (5) <80% HR_{PEAK}. Then, the frequency of occurrence (%) of each activity category was calculated.

Blood was collected from the athletes' earlobes to measure lactate concentration. The lactate concentration in the blood was analyzed by the electrochemical method, using a YSI Model 23l Lactate Analyzer (Yellow Springs, US), which had been calibrated previously. The lactate collections took place before the start of the activity, shortly after each round, and 3 and 5 min after the last round. During the interval between rounds, the athletes remained in standing position. The oxygen consumption measurement in a combat simulation and during rest was done breath-by-breath with the $K4b^2$ (Cosmed, Italy), which has previously been validated (Hausswirth et al. 1997). The athlete remained with the equipment during the entire combat and for 6 min after the activity ended. The mean oxygen consumption (VO_{2MEAN}) was calculated as the average VO_2 during the entire time of the round. Because the gas analyzer used is telemetric one researcher made specific marks to register the beginning and ending of combat phases during all procedures. Thus, VO_2 during the interval ($VO_{2INTERVAL}$) between rounds was also reported.

Energy system contribution calculation

Estimates of aerobic, anaerobic lactic, and anaerobic alactic system use were carried out through the measurement of oxygen consumption during activity, peak blood lactate concentration, and the fast phase of excess oxygen consumption after exercise ($EPOC_{FAST}$), respectively.

Aerobic energy (W_{AER}) was estimated by subtracting VO_{2REST} from VO_2 during the rounds by the trapezoidal method (a method used to calculate the area under the curve, i.e., the curve is divided into pieces and then the sum of each trapezoid is calculated to estimate the integral) (Bertuzzi et al. 2007; Mello et al. 2009). Rest oxygen consumption (VO_{2REST}) was determined in the standing position, with the last 30 s of a 5-min period used as a reference. The anaerobic alactic system contribution (W_{PCR}) was estimated considering the oxygen consumption during the interval between rounds and the $EPOC_{FAST}$ after the third round (Beneke et al. 2002, 2004; Bertuzzi et al. 2007; Mello et al. 2009). In the present study, we fitted the kinetics of post-match oxygen consumption to bi- and mono-exponential models and observed that the slow component of the bi-exponential model was negligible. Thus, the post-match breath-by-breath VO_2 data were fitted to a mono-exponential model and W_{PCR} was obtained by calculating the integral of the exponential part (Origin 6.0, Microcal, Massachusetts, USA).

The participation of the anaerobic lactic system ($W_{[La^-]}$) was calculated as the lactate concentration after combat, assuming that the accumulation of 1 mmol L^{-1} $[La^-]$ is equivalent to 3 ml O_2 kg^{-1} of body mass (di Prampero and Ferretti 1999). The caloric quotient of 20.92 kJ (Gastin 2001) was used in all three different energy systems. The Δ of lactate (ΔLa^-) was calculated as the lactate concentration after the round, minus the lactate concentration at the beginning of the round.

Total metabolic work (W_{TOTAL}) was calculated as the sum of the three energy systems ($W_{AER} + W_{PCR} + W_{[La^-]}$). In this way, the contribution of the three energy systems was also expressed in the W_{TOTAL} percentage.

Video analysis

The recorded images were analyzed using the Sony Vegas Pro 8.0® software, according to the criteria of Santos et al. (2011). Time–motion analyses were conducted in an attempt to calculate work/rest ratios for each match. The events were measured in seconds and tenths of seconds, using the marking tool in the analysis software. An attack was considered the time from the beginning of a foot or hand movement in the direction of the opponent until the athlete stopped his attack movement or was unable to continue attacking (due to a fall or referee pause). Step was defined as the entire period between attacks when there was no break in combat. Pause was defined as the stops in combat solicited by the referee. A single researcher who is highly experienced and familiarized with taekwondo matches conducted all the video analysis.

Step time was added to the referee pause times to define the period without attack (PWA). Thus, the PWA was the entire time without attack, together with the stopwatch stop time called out by the referees. Attack (AT) was considered the total time during which one of the athletes attempted to attack or succeeded in attacking his opponent. The analyses showed a high rate of intra-class correlation (ICC): 0.93. Similar analyses in other combat sports have been presented as objective (Marcon et al. 2010; Salvador et al. 1999), given that the actions were classified as serial and allow the easy identification of their beginning and end.

Statistical analysis

The data were analyzed using SPSS 17.0 (SPSS Inc., Chicago, USA) software. The descriptive analysis involved the calculation of the mean and standard deviation. The distribution of the data was analyzed using the Shapiro–Wilk test, which showed a normal Gaussian distribution. The wholeness of the data for all study variables was verified in accordance with the Mauchly test, and the Greenhouse-Geisser adjustment was used when necessary (Zar 1999). The variables were compared using a one-way analysis of variance (ANOVA) with repeated measurements. When necessary, the Bonferroni multiple comparison test was

Table 1 Physiological responses during a taekwondo combat ($n = 10$)

	Round 1	Round 2	Round 3	Total
HR_{PEAK} (bpm)	172 ± 7*,†	183 ± 7†	189 ± 4	181 ± 9
HR_{MEAN} (bpm)	156 ± 9*,†	169 ± 9†	175 ± 10	167 ± 12
VO_{2MEAN} (L min^{-1})	3.0 ± 0.4*,†	3.5 ± 0.4	3.6 ± 0.4	3.3 ± 0.5
VO_{2MEAN} (mL kg^{-1} min^{-1})	44.4 ± 6.2*,†	52.1 ± 5.9	53.4 ± 5.9	49.9 ± 7.1
$[La^-]_{AFTER\ ROUND}$ (mmol L^{-1})	4.2 ± 0.7*,†	5.9 ± 1.2	6.6 ± 1.1	5.6 ± 1.3
$[La^-]_{PEAK}$ (mmol L^{-1})	4.2 ± 0.7*,†	5.9 ± 1.2	7.0 ± 1.5	5.7 ± 1.6
Δ[La] (mmol L^{-1})	2.7 ± 0.9†	1.7 ± 1.0	1.3 ± 1.1	1.9 ± 1.1

Data are reported as mean and standard deviation

HR_{PEAK} peak heart rate, HR_{MEAN} mean heart rate, VO_{2MEAN} mean oxygen uptake, $[La^-]_{AFTER\ ROUND}$ immediately post round blood lactate; $[La^-]_{PEAK}$ highest post-round blood lactate concentration (for rounds 1 and 2 only one measurement was conducted and this value is the same presented in $[La^-]_{AFTER\ ROUND}$), *Δ[La]* blood lactate concentration after the round minus blood lactate at the beginning of the round

* Different from round 2 ($P < 0.05$)

† Different from round 3 ($P < 0.05$)

used in order to identify possible differences between rounds. The statistical significance level used was $P < 0.05$.

Results

The heart rate, oxygen consumption and blood lactate concentration results are described in Table 1.

The HR_{PEAK} varied between rounds ($F_{2,18} = 43.2$; $P < 0.001$; $\eta^2 = 0.88$), with the values in the first round being lower than those in the last two ($P < 0.001$ for both comparisons), and the values of the second round ($P < 0.05$) being lower than those of the third round. The HR_{MEAN} also varied between rounds ($F_{2,18} = 29.5$; $P < 0.001$; $\eta^2 = 0.77$), with values in the first round lower than those in the second and third rounds ($P < 0.001$ for the two comparisons). Athletes stayed 20.4 ± 6.8% of time at <80% HR_{PEAK}, 9.6 ± 8.8% of time at 81–84% HR_{PEAK}, 17.2 ± 6.3% of time at 85–89% HR_{PEAK}, 26.1 ± 7.2% of time at 90–94% HR_{PEAK} and 28.1 ± 8.9% of time at >95% HR_{PEAK}. Differences ($F_{4,36} = 7.43$; $P < 0.001$; $\eta^2 = 0.45$) emerged between intensity of efforts. Further analysis indicated difference ($P < 0.01$) between the time spent at 81–84% HR_{PEAK} and >95% HR_{PEAK}. In particular, during the match athletes spent more than 54% of the time working at HR higher than 90% HR_{PEAK}.

The absolute VO_{2MEAN} varied between rounds ($F_{2,18} = 48.6$; $P < 0.001$; $\eta^2 = 0.85$), with values lower in the first round as compared to the second and third rounds ($P < 0.001$ for both comparisons). The same was true for relative VO_{2MEAN} ($F_{2,18} = 50.8$; $P < 0.001$; $\eta^2 = 0.85$), with lower values in the first round as compared to the second and third rounds ($P < 0.001$ for both comparisons). $VO_{2INTERVAL}$ was 38.5 ± 6.7 mL kg^{-1} min^{-1} after the first round and 40.3 ± 6.3 mL kg^{-1} min^{-1} after the second round. There was no difference in $VO_{2INTERVAL}$ between these two periods.

The blood lactate immediately after each round ($[La^-]_{AFTER\ ROUND}$) also differed between rounds ($F_{2,18} = 36.8$; $P < 0.001$; $\eta^2 = 0.80$), with values lower in the first round than in the second and third rounds ($P < 0.05$ for the two comparisons). The $[La^-]_{PEAK}$ was also affected by round ($F_{2,18} = 25.9$; $P < 0.001$; $\eta^2 = 0.86$), with values lower in the first round than in the second and third rounds ($P < 0.05$ for the two comparisons). The Δ $[La^-]$ exhibited differences ($F_{2,18} = 4.4$; $P < 0.05$; $\eta^2 = 0.33$) between rounds with higher values in the first round than in the third ($P < 0.05$).

Relative (%) and absolute (kJ) energy contributions are presented in Table 2. The amplitude and the time constant of post match VO_2 were 2,773 ± 636 mL and 63.8 ± 24.9 s, respectively.

There were significant differences between the percentage contributions of the three systems ($F_{2,18} = 270.2$; $P < 0.001$; $\eta^2 = 0.97$) with the aerobic system contributing more than the anaerobic alactic system, and the anaerobic lactic system contributing the least ($P < 0.001$ in all comparisons).

The absolute aerobic energy cost and aerobic cost relative to time (kW) were not the same for all rounds ($F_{2,18} = 22.4$; $P < 0.001$; $\eta^2 = 0.71$ and $F_{2,18} = 15.4$; $P < 0.01$; $\eta^2 = 0.63$, respectively), with lower values observed in the first in relation to the second and third rounds ($P < 0.001$ for the two comparisons). There was no difference in aerobic percentage contribution between the rounds.

No between-round differences were seen in anaerobic alactic contribution in absolute (kJ), relative to time (kJ min^{-1}) or relative to total (%) contributions. However, a round effect of round was observed for the anaerobic

Table 2 Metabolic responses of taekwondo combat simulation on the three rounds ($n = 10$)

	Round 1	Round 2	Round 3	Total
Aerobic				
W_{AER} (kJ)	98 ± 15*,†	127 ± 14	134 ± 18	120 ± 22
Relative (%)	62 ± 6	70 ± 6	67 ± 12	66 ± 6
Relative for the time (kW)	0.77 ± 0.13*,†	0.99 ± 0.16	1.02 ± 0.16	0.93 ± 0.18
Anaerobic Alactic				
W_{PCR} (kJ)	49 ± 11	49 ± 10	63 ± 32	54 ± 21
Relative (%)	31 ± 7	26 ± 5	30 ± 12	30 ± 6
Relative for the time (kW)	0.38 ± 0.07	0.38 ± 0.09	0.48 ± 0.23	0.41 ± 0.15
Anaerobic Lactic				
$W_{[La^-]}$ (kJ)	11 ± 4†	7 ± 4	6 ± 5	8 ± 5
Relative (%)	7 ± 2†	4 ± 2	3 ± 3	4 ± 2
Relative for the time (kW)	0.09 ± 0.03†	0.06 ± 0.03	0.04 ± 0.04	0.06 ± 0.04
W_{TOTAL} (kJ)	158 ± 17*,†	183 ± 17	203 ± 29	181 ± 28
W_{TOTAL} relative for the time (kW)	1.24 ± 0.14*,†	1.43 ± 0.19	1.54 ± 0.22	1.40 ± 0.22

Data are reported as mean and standard deviation

W_{AER} aerobic energy, W_{PCR} anaerobic alactic energy, $W_{[La^-]}$ anaerobic lactic energy, W_{TOTAL} total metabolic work ($W_{AER} + W_{PCR} + W_{[La^-]}$)

* Different from the *round* 2 ($P < 0.05$)

† Different from the *round* 3 ($P < 0.05$)

Table 3 Attack time, number of attacks, total time of attacks, total time without attacks, ratio between attacks and time without attacks, and ratio between total time without attacks and number of attacks ($n = 10$)

	Round 1	Round 2	Round 3
Attack time (s)	0.72 ± 0.11	0.73 ± 0.10	0.68 ± 0.11
Number of attacks (n)	17 ± 5	17 ± 6	18 ± 3
Sum of attacks time (s)	13 ± 4	13 ± 4	12 ± 3
Sum of time without attacks (s)	109 ± 7	107 ± 4	107 ± 4
Attacks/without attacks ratio	0.12 ± 0.05	0.12 ± 0.04	0.12 ± 0.04
Sum of time without attacks/number of attacks ratio	7 ± 2	7 ± 3	6 ± 1

Data are reported as mean and standard deviation

lactic system contribution in absolute lactic energy cost ($F_{2,18} = 4.0$; $P < 0.05$; $\eta^2 = 0.31$), in percentage of the total ($F_{2,18} = 8.3$; $P < 0.01$; $\eta^2 = 0.48$), and relative to time ($F_{2,18} = 4.5$; $P < 0.05$; $\eta^2 = 0.34$), with higher values in the first round than in the third round for all the variables.

Both absolute energy cost and energy cost relative to time varied between rounds ($F_{2,18} = 10.1$; $P < 0.01$; $\eta^2 = 0.53$; $F_{2,18} = 7.3$; $P < 0.05$; $\eta^2 = 0.45$, respectively), with lower values in the first round than in the last two ($P < 0.05$).

Technical actions and the time spent on each phase in the three rounds are described in Table 3.

In the analyses of technical actions, no between-round differences were identified in attack time, total time without attack, total attack time, number of attacks or in the time without attack/number of attacks variables.

Discussion

To the best of our knowledge, this is the first study that has reported energy system contributions during simulated taekwondo combat. The contributions of the different energy systems reported in the present study show that the aerobic system is predominant in taekwondo combats (three 2-minute rounds with 1-minute intervals between the rounds), contributing 66 ± 6% of the total energy cost of combat. In contrast, the anaerobic alactic and lactic systems contributed 30 ± 6 and 4 ± 2% of the total energy expenditure, respectively. The aerobic predominance is probably a consequence of the low frequency of high intensity blows relative to the pauses and step movements that is characteristic of the sport (1:7). Therefore, although the acyclic actions of high intensity are maintained by the anaerobic alactic system, the restoration of its substrates (especially creatine phosphate stores) and the activity in the remaining time are maintained at the cost of the oxidative system. These results support the proposition presented by Matsushigue et al. (2009) but does not support the inference that glycolysis predominates during taekwondo matches, as suggested by Markovic et al. (2008). In contrast, Markovic et al. (2005) pointed out that the performance of taekwondo athletes depends primarily on anaerobic alactic power, explosive power expressed in the stretch–shortening cycle movements, agility and aerobic power, which agrees with our metabolic profile of the taekwondo match.

Although there was a high variability in energy expenditure when absolute values were presented, the relative contribution was more homogeneous. This high variability in absolute values is due to the inclusion of athletes from different weight categories, as well as different age, in our sample and has been reported in taekwondo athletes (Bridge et al. 2009; Markovic et al. 2008). However, the more homogeneous response in relative values in the present study indicates that experienced athletes competing internationally in taekwondo present similar physiological and metabolic responses when the percentage of total energy contribution is considered.

An increase in total absolute energy cost was observed over the course of the combat. This indicates that there was a greater energy demand for the completion of high intensity actions (blows), as the match progressed, even though there was no increase in the number of technical actions. This can be attributed to an increase in aerobic contribution, because this system is responsible for the restoration of homeostasis during periods of low intensity efforts (Glaister 2005). This same difference was observed when total energy cost relative to time was analyzed. We suggest three factors that could be related to the increase in physiological demand during the match. First, athletes may have been under thermal stress due to protective garments. The taekwondo uniform and the gas analyzer worn by the athletes could have contributed to increase their temperature and, consequently, increased the physiological strain across rounds. Second, the increase in physiological demand could be due to insufficient recovery between rounds. As only 1-minute interval is allowed during the taekwondo matches, it is probable that only a partial recovery was attained; complete ressynthesis of creatine phosphate (which is important for high-intensity actions performed during attack and defensive technique applications) requires more time and removal of other metabolites as H^+ and Pi are also longer than this period. Additionally, this interval seems to be insufficient to reduce the cardiovascular and thermoregulatory strain from the previous round, as evidenced by the high oxygen consumption during the interval between rounds. A third possibility is that match strategy led to increased demand in each round. It is common for taekwondo athletes to save energy for the last period of the combat when the most decisive attacks normally occur, resulting in an increase in the metabolic response during the last round (Chiodo et al. 2011a).

The data in the present study indicate that the glycolytic system contribution was larger in the first round than in later rounds, with a progressive decrease in the second to the third round. These findings are in accordance with previously published studies that have shown an increase in aerobic contribution and a decrease in glycolytic activity in maximum intermittent exercises (Gaitanos et al. 1993; Glaister 2005).

Moreover, results show a lower percentage of aerobic metabolism contribution when compared with karate, which uses 77.8, 16.0 and 6.2% from the aerobic, anaerobic alactic and anaerobic lactic systems, respectively (Beneke et al. 2004). This difference could be ascribed to the general characteristics of the two combat sports. For example, karate makes more use of the upper limbs than taekwondo, and there is a significant difference in match duration between these two sports. In another analysis of karate, Doria et al. (2009) demonstrated that the *kumite* received 70% of its energy from aerobic metabolism, 20% from alactic metabolism and 10% from lactic metabolism. Crisafulli et al. (2009) investigated the participation of the different energy systems during a combat simulation (three 2-min duration rounds with 1-min of rest between rounds), highlighting in muay thai, which has technical actions similar to those in taekwondo (kicks and punches). Also like our taekwondo matches, the muay thai matches analyzed consisted of three 2-minute rounds with 1-minute of rest between rounds. These authors again found that aerobic metabolism predominated, with anaerobic metabolism recruited mainly during the first round and progressively reduced in subsequent rounds. Our data also confirm the findings by Crisafulli et al. (2009) in terms of the decreased contribution of anaerobic metabolism throughout the rounds.

The effort-pause ratio observed in our study was $\sim$1:7. These data are identical to those reported by Santos et al. (2011), in an analysis of high-level taekwondo competitions (Olympic Games and World Championship). Studies of other taekwondo styles, i.e., International Taekwondo Federation (Heller et al. 1998) and Songahm Taekwondo (Matsushigue et al. 2009), reported different effort-pause ratio; values of 1:3 to 1:4 were observed by Heller et al. (1998) during match simulations by athletes from the Czech National Team, while Matsushigue et al. (2009) found a ratio of 1:6. These results indicate that the athletes of the present study underwent high intensity situations at the same proportion observed in real competition or combat simulation. The length of low-intensity activity relative to the intense effort actions might be sufficient for the recovery of phosphocreatine degraded during explosive movement.

Although the effort:pause ratio and the number of technical actions were similar to those reported in other studies (Matsushigue et al. 2009; Santos et al. 2011) the use of the gas analyzer could inhibit the intensity of attack and defensive actions. Despite this more controlled technique application intensity, blood lactate concentration measured at the end of the combat was higher than that measured during other simulation (2.9 ± 2.1 mmol L^{-1}; Butios and Tasika 2007), and was similar to that measured in real taekwondo competition (7.0 ± 2.6 mmol L^{-1}; Chiodo et al. 2011a), though slightly lower than that reported in other simulations (10.2 ± 1.2 mmol L^{-1}; Bouhlel et al. 2006) and for an international level taekwondo competition (11.9 ± 2.1 mmol L^{-1}; Bridge et al. 2009). A more direct comparison is difficult to conduct, because these studies did not report the number of technical actions performed by the athletes.

An increase in heart rate values was observed over the course of the combat. This suggests that cardiovascular demands increase through the rounds. However, this difference was not verified in relation to the number of higher intensity technical actions in the three rounds. An increase in cardiovascular demand per round has already been identified in other studies in taekwondo (Bridge et al. 2009). The heart rates collected in the present study are lower than those reported by Bouhlel et al. (2006) in simulated competition (197 ± 2 bpm). This may be due to the changes in WTF regulations since that study was conducted (the duration of each round was reduced from three minutes in that study to two minutes in the present study). Bridge et al. (2009) studied the cardiovascular responses in an international competition with the same rule as the present study and reported slightly higher values (182 ± 6 bpm) than those found in our study. Thus, our simulated combat produced lower cardiovascular demand that previously reported in international level competition. In addition, to compare HR responses among athletes, intensities of efforts during fighting were estimated from individual peak HR values recorded during match simulation. Most of the time (>54%) athletes presented values higher than 90% HR_{PEAK}, demonstrating the high cardiovascular strain of taekwondo match as previously reported (Capranica et al. 2011; Chiodo et al. 2011b). Furthermore, the only difference in time spent at different percentages of effort was between 81 and 84% HR_{PEAK} and >95% HR_{PEAK}, indicating that just after the beginning of each round, when the HR is commonly below 80% HR_{PEAK}, there is a rapid increase toward higher values with a small time at this range.

In conclusion, different energy contributions were estimated during taekwondo combat simulation in accordance with official WTF regulations. The performance of higher intensity technical actions, in conjunction with active recovery periods, caused the aerobic system to predominate although decisive actions were maintained by the elevated activation of the anaerobic alactic system. Considering that the scores during the match are obtained through high-intensity actions, which are maintained by the anaerobic alactic system, and considering that creatine phosphate is resynthesized by the aerobic system, coaches should focus training stimuli on this metabolic system and limit training tasks directed to the anaerobic lactic metabolism, at least during the competitive phase of the training periodization. Because taekwondo athletes typically perform four matches during competitions and the recovery process is an important aspect for success in this sport (Chiodo et al. 2011a), future studies should use the same methods applied in the present investigation to verify the relationship between different physical fitness variables and the energy system contributions during competition and to different recovery strategies between matches.

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