

VERTICAL JUMP PERFORMANCE AND BLOOD AMMONIA AND LACTATE LEVELS DURING TYPICAL TRAINING SESSIONS IN ELITE 400-m RUNNERS

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ABSTRACT

Gorostiaga, EM, Asiáin, X, Izquierdo, M, Postigo, A, Aguado, R, Alonso, JM, and Ibáñez, J. Vertical jump performance and blood ammonia and lactate levels during typical training sessions in elite 400-m runners. *J Strength Cond Res* 24(x): 000–000, 2010—This study described the effects of 6 typical high-intensity intermittent running training sessions of varying distances (60–300 m) and intensities (80–105% of the individual best 400-m record time) on blood ammonia and lactate concentration changes and on vertical jumping height, in twelve 400-m elite male runners. At the end of the training sessions, similar patterns of extremely high blood lactate (14–23 mmol·L⁻¹) and ammonia levels (50–100 μmol·L⁻¹) were observed. Vertical jumping performance was maintained during the initial exercise bouts up to a break zone of further increase in the number of exercise bouts, which was associated, especially in subjects with the highest initial vertical jump, with a pronounced decrease (6–28%) in vertical jumping performance, as well as with blood lactate concentrations exceeding 8–12 mmol·L⁻¹, and blood ammonia levels increasing abruptly from rest values. This break zone may be related to signs of energetic deficiency of the muscle contractile machinery associated with the ability to regenerate adenosine triphosphate at high rates. It is suggested that replacing some of these extremely demanding training sessions with other intermittent training sessions that preserve muscle

generating capacity should allow elite athletes to practice more frequently at competitive intensity with lower fatigue.

KEY WORDS sprint training, track and field, metabolic response, explosive force

INTRODUCTION

Four hundred-meter running is an extremely demanding event that maximally stimulates the anaerobic and aerobic energy production systems because at the end of the race, muscle phosphocreatine (PCr) stores are almost completely depleted (15), muscle and blood lactate concentrations attain an individual maximum level up to 15–25 mmol·L⁻¹ (15), and oxygen uptake values reach a very high percentage of individual maximal oxygen uptake (30). Limited scientific-based information is available concerning the type of training method required to optimally increase 400-m running performance in elite athletes. An adapted approach to begin building a scientific-based training method to optimally increase 400-m running performance is to describe and analyze the power output and metabolic responses of currently accepted training sessions, as used by elite athletes.

It is known that intermittent exercise with short bouts (60–300 m) of heavy intensity exercise (80–105% of the individual best 400-m record time) separated by recovery periods of varying length (3–15 minutes) are habitually used (2–4 sessions·week⁻¹) by elite 400-m athletes during training sessions. In terms of energy status, 2 main exercise modes of intermittent exercise can be differentiated (1,2,26): (a) those characterized by blood lactate levels not exceeding 8–12 mmol·L⁻¹ (1,2,25,26) while energy status (25,26) and maximal running velocity or muscle generating capacity (1,2) are maintained; and (b) those characterized by a continuous increase in blood lactate that may reach values up to 13–30 mmol·L⁻¹ at the end (1,2,26), leading to a significant decrease in maximal running velocity or muscle generating capacity (1,2) and signs of energetic deficiency and delayed functional recovery (1,2,25).

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The results of this study do not constitute endorsement of the product by the authors of the National Strength and Conditioning Association. Address correspondence to Dr. Esteban M. Gorostiaga, egorosta@cnavarra.es.

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The training sessions leading to high blood lactate levels (13–30 mmol·L⁻¹) are very popular among 400-m coaches, and they form the basis for summary material presented in education and coaching literature (30) because they reproduce the physiological responses observed during official 400-m running competitions in elite athletes (19). However, it is known that frequently repeated sessions that induce this extreme metabolic stress may lead to a chronic reduction in resting adenosine triphosphate (ATP) concentration, an accumulated loss of adenine nucleotides (1), and an increased production of superoxide radicals, which may ultimately cause muscle damage (29). This extreme and frequent disruption of the energy balance in the muscle cell, reflected by extensive ATP depletion, may place a cumulatively greater stress on the cells and may be associated with an inordinately long recovery time requirement (14) and impairments in muscle power generation and fatigue, which could potentially affect subsequent 400-m performance. The other mode of intermittent exercise, characterized by blood lactate levels not exceeding 8–12 mmol·L⁻¹ (1,2,25,26) while energy status (25,26) and maximal running velocity or muscle generating capacity (1,2) are maintained, is far from exhausting (1,2) and should allow athletes to practice running at a competitive intensity of exercise and refine their technique with lower fatigue. However, this type of exercise does not replicate the physiological responses observed during official 400-m running competitions in elite athletes (19).

Taking the above physiological characteristics of these 2 types of intermittent exercise into account, it is conceivable that both exercise types should be included in the training program of elite 400-m runners. However, the question is, which combination of these 2 types of intermittent exercises is optimal to elicit the greatest rate of improvement in 400-m running performance?

In such a situation, it is of interest to analyze how coaches combine these 2 modes of intermittent exercise during typical training sessions performed by elite 400-m runners. It was the purpose of this study, therefore, to describe the metabolic and muscle power output changes that occur during typical high-intensity intermittent training sessions of varying duration and intensity, used by elite 400-m runners to enhance their performance. The metabolic characteristics of the training sessions were monitored by measuring blood ammonia and lactate levels, whereas power output production was monitored by measuring vertical jumping height. These measurements are of interest because they allow a differentiation to be made between the 2 main exercise modes of intermittent exercise cited above and because they are considered to indirectly reflect the degree of anaerobic glycolysis activation (20) (blood lactate), muscle ammonia formation, and muscle ATP depletion (blood ammonia) (17,31) and the capability of the leg extensor muscles to generate mechanical power (vertical jumping height). Another purpose of this study was to investigate the relationships between changes in force production and blood lactate and

in blood ammonia concentrations observed during the training sessions.

METHODS

Experimental Approach to the Problem

The present study afforded an opportunity to describe the metabolic changes resulting from high-intensity training sessions while monitoring blood lactate and ammonia levels and the time course of the decline in muscle power output during training sessions examined in 400-m elite runners. The training sessions were devised in consultation with coaches to represent training sessions that 400-m runners usually undertake during the precompetition or competition phase. A description of the metabolic response to training sessions in elite 400-m runners may lead to a better understanding of the factors that limit performance and would help to compose a scientific-based well-balanced training program that improves 400-m running performance. The mechanical behavior of the leg extensor muscles during natural motion, as occurs during vertical jump, was evaluated because 400-m running performance is clearly limited by the decline of muscular explosive force (22). Blood lactate and ammonia levels were measured because they are considered to mainly be an effect of the degree of anaerobic glycolysis activation (20) and muscle ammonia formation as well as muscle ATP depletion (blood ammonia) (17,29), respectively. Measuring these variables also allows differentiation between types of intermittent training sessions in terms of energy status (1,2,26). The hypotheses were as follows: (a) Elite coaches combine the 2 modes of intermittent exercise sessions in a balanced way; (b) In line with previous investigations (5,24), runners showing the greatest initial vertical jumping height are more prone to fatigue with successive sprints than runners with lower capability of leg extensor muscles to generate mechanical power; and (c) In line with studies performed with recreationally active subjects (28) and low-level 400-m runners (27), a significant relationship should be observed among blood lactate, blood ammonia, and leg extensor power production in elite 400-m runners during successive exercise bouts. In this case, the relationships should allow for elite 400-m runner coaches to indirectly estimate the degree of blood ammonia and blood lactate accumulation during high-intensity intermittent exercises from changes in vertical jump values.

Subjects

Twelve male athletes, 400-m runners ($n = 10$) and 400-m hurdlers ($n = 2$), who were specialists at the national and international level, participated in the study. The subjects' mean ($\pm SD$) age, height, and body mass were 23.6 \pm 2.7 years, 181.8 \pm 4.9 cm, and 72.5 \pm 5.4 kg, respectively. No general clinical examination was carried out, but all subjects were medically examined annually. The subjects had trained for about 2–4 hours a day, 4–6 days a week all the year around, for 4–10 years. The study was conducted in

December and January during an indoor season and during the precompetition or competition phase of their yearly program, at a time when most of the athletes were at a high level of competitive fitness. At the time of these observations, the track athletes had completed between 2 and 4 months of training.

Selected individual characteristics of all the athletes are presented in Table 1. The athletes were ranked among the 17 best Spanish 400-m runners and 400-m hurdlers. Of these, 8 were ranked among the 10 best Spanish 400-m runners and the 2 hurdlers were ranked among the 3 best Spanish 400-m hurdlers. Their 400-m running and 400-m hurdle season's best performances ranged between 45.33 and 47.89 seconds and between 51.36 and 51.59 seconds, respectively. The average ($\pm SD$) 400-m record of the subjects (47.0 ± 0.7 and 51.5 ± 0.2 seconds for 400-m runners and 400-m hurdlers, respectively), expressed as a percentage of the present World Record, was 92% with a range of 90–95%. At time of the present study, 5 of the athletes participated in the Olympic Games and in the World Championship. All of them were professional athletes.

Before participating, the subjects and coaches were informed in detail about the experimental procedures and the possible risks and benefits of the study and gave their consent for the participation in the present investigation, which was approved by the Institutional Review Committee of the Instituto Navarro de Deporte y Juventud and carried out in conformance with the policy statement of the American College of Sports Medicine on research with human subjects. Each subject signed a written informed consent form before participation in the study. The training sessions were devised in consultation with coaches to represent training sessions that 400-m runners usually undertake during the precompetition or competition phase.

TABLE 1. Individual physical characteristics and competitive distance of the subjects.

Subject	Height (cm)	Body mass (kg)	Age (y)	Distance (m)
1	183	75	22	400 (hurdles)
2	183	76	21	400
3	183	73	28	400
4	179	62	25	400
5	180	77	21	400
6	183	71	25	400
7	188	77	21	400
8	173	64	24	400
9	178	68	25	400
10	178	74	22	400
11	192	80	20	400 (hurdles)
12	182	74	28	400

Procedures

The subjects were asked not to engage in any moderate or heavy intensity exercise during the day before the experiment and to have breakfast at least 2 hours before the beginning of the warm-up period. All athletes had experience with the exercises analyzed. All training sessions were carried out between 10:00 and 14:00 hours on an outdoor 400-m Tartan track with a mondo surface certified by the Spanish Track and Field Federation. Before the high-intensity running exercises, the subjects had a light 20-minute warm-up of continuous submaximal running, stretching exercises, and short bursts of acceleration.

Table 2 shows the characteristics of the 6 types of training sessions. Each athlete attended 1 training session, and the athletes ran in pairs. For each athlete, the average relative intensity of each running training session was expressed as a percentage index of the average velocity sustained during his best 400-m running performance in the preceding season ($\%V_{400}$). The running training sessions analyzed belonged to 2 classic categories of training methods used by sprint athletes: speed training (training sessions 1 and 2; short sprints of 20–100 m at velocity higher than V_{400}), and intensive interval training (training sessions 3–6; runs of 200 and 300 m at a velocity of 92% and 80–87%, respectively, of $\%V_{400}$).

Running bouts were interposed with rest periods ranging from 3 to 8 minutes. All runs were performed from a standing start position. The relief periods between successive work intervals for all groups consisted of walking or standing in a resting position. Blood samples were drawn at rest between 2 and 3 minutes after several running bouts for ammonia and lactate determination (see Table 2 for details). The subjects performed 2 maximal voluntary countermovement vertical jumps at rest, 1 minute after each running bout, except for the first and the third running bout in training session 1. The test-retest intraclass correlation coefficients of the testing procedure variables used in this study were greater than 0.91, and the CV ranged from 0.9 to 7.3%.

Physical Characteristics

The anthropometric variables of height (m) and body mass (kg) were measured in each subject (Table 1). Height and body mass measurements were made on a leveled platform scale with an accuracy of 0.01 kg and 0.01 m, respectively.

Sprint Time. The running time over each work period distance for each athlete was measured by stopwatch by at least 2 national federation coaches. The average of both times was used for further analysis.

Jumping Test. Subjects were asked to perform a maximal countermovement vertical jump on a contact platform (Newtest OY, Oulu, Finland). Using a preparatory countermovement, subjects performed the jump from an extended leg position, down to 90° knee flexion and then immediately followed this with a concentric action where the subject

TABLE 2. Characteristics of the training sessions.*

Type of training session	Subject number	Running bouts (sets × distance) (m)	Recovery between bouts (min)	Running velocity (% V_{400}/V_{400h}^*)	Blood lactate concentration at recovery	Blood ammonia concentration at recovery	Height in Counter Movement Jump at recovery
1	1,2	3 × 60	4	103% and 112%*	3 min (bouts 6,9)	3 min (all bouts except 2)	1 min (all bouts except 1,3)
2	3,4	3 × 80	6	105% and 115%*			
3	5,6	3 × 100	8	104% and 115%*			
4	7,8	6 × 100	5	101% and 103%	3 min (bouts 2, 4, 6)	3 min (bouts 1, 3, 5)	1 min (all bouts)
5	9,10	8 × 200	3	92% and 91%	3 min (bouts 8)	2 min (bouts 1,3,5,7,8)	1 min (all bouts)
		6 × 300	6	87% and 86%	3 min (all bouts)	2 min (all bouts)	1 min (all bouts)
		3 × 3 × 300	8 between sets; 4 between repetitions	86% and 87%	3 min (bouts 3, 6, 9)	2 min (all bouts)	1 min (all bouts)
6	11,12	12 × 300	3	91%* and 80%	3 min (bouts 12)	2 min (bouts 1, 3, 5, 7, 9, 10, 11, 12)	1 min (all bouts)

*% V_{400} : average velocity during the running bouts expressed as a percentage of the best 400-m running performance (% V_{400}) or the best 400-m hurdles performance (% V_{400h}).

jumps for maximal height. Subjects were instructed to keep their hands on their hips throughout the entire jump to minimize lateral and horizontal displacement during performance. Trunk flexion and extension were kept to a minimum during the performance. The jumping height was calculated from the flight time (6). Two maximal jumps were recorded, interspersed with approximately 10-second rest between jumps, and the best reading was used for further analysis.

Blood Lactate Concentration. A hyperemic ointment (Finalgon; Boehringer, Ingelham Rhein, Germany) was applied to the earlobe 10 minutes before initial blood sampling. Capillary blood samples for the determination of whole blood lactate concentrations were obtained from hyperemic earlobe. Samples for whole blood lactate determination (100 μ L) were collected in a preservative collection kit (YSI Preservative Collection Kit; Yellow Springs Inc., Yellow Springs, Ohio, USA), stored at 4°C, and analyzed within the following 24–72 hours (1500 Sport L-Lactate Analyzer, YSI). The blood lactate analyzer was calibrated after every fifth blood sample dose with 3 known controls (5, 15, and 30 $\text{mmol}\cdot\text{L}^{-1}$).

Blood Ammonia Concentration. After cleaning and puncturing, a single 20 μ L of whole blood sample was taken from hyperemic earlobe with an Eppendorf vari pipette and immediately analyzed with an ammonia checker (BAC) II (model AA-4120; Kyoto Daiichi, Kayaku Co., Ltd., Kyoto, Japan and Menarini Diagnostic, Italy) with a simple volume of 20 μ L of blood. This analyzer uses a reflectometer to optically measure the reflection intensity (45°) of reagent color reaction in bichromatic mode and was calibrated before and after every test with a known control (58.7 $\mu\text{mol}\cdot\text{L}^{-1}$).

Statistical Analyses

Standard statistical methods were used to calculate the mean and *SDs*. Coefficient of determination (R^2) was used to determine associations among blood lactate, blood ammonia, and vertical jump values. Linear or nonlinear regressions were determined using either a linear or a second-degree polynomial form. A second-degree polynomial form was accepted if it resulted in a significant reduction in error variance as compared with the linear solution. Statistical power calculations for this study ranged from 0.75 to 0.80. The test-retest intraclass correlation coefficients for all power and metabolic variables were greater than 0.92, and the coefficient of variation (CV) ranged from 0.9 to 2.0%. The $p \leq 0.05$ criterion was used to establish statistical significance.

RESULTS

Figures 1 and 2 show the individual values for blood lactate and ammonia concentrations and for height in vertical jump during the 6 types of training sessions examined.

Training Session 1

Sprint running times in 60, 80, and 100 meters were 6.88 ± 0.08 , 8.94 ± 0.06 , and 11.23 ± 0.13 seconds, respectively.

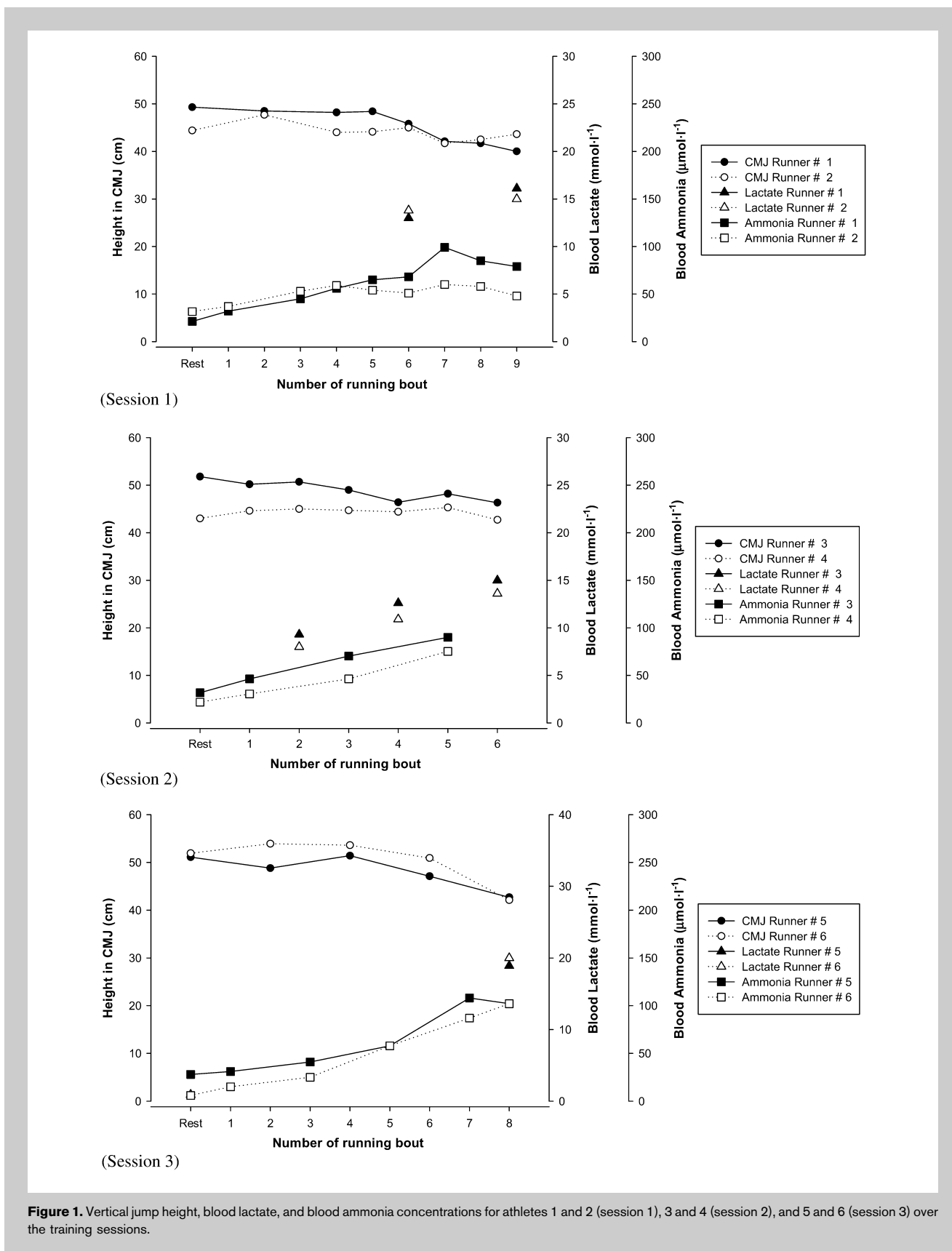


Figure 1. Vertical jump height, blood lactate, and blood ammonia concentrations for athletes 1 and 2 (session 1), 3 and 4 (session 2), and 5 and 6 (session 3) over the training sessions.

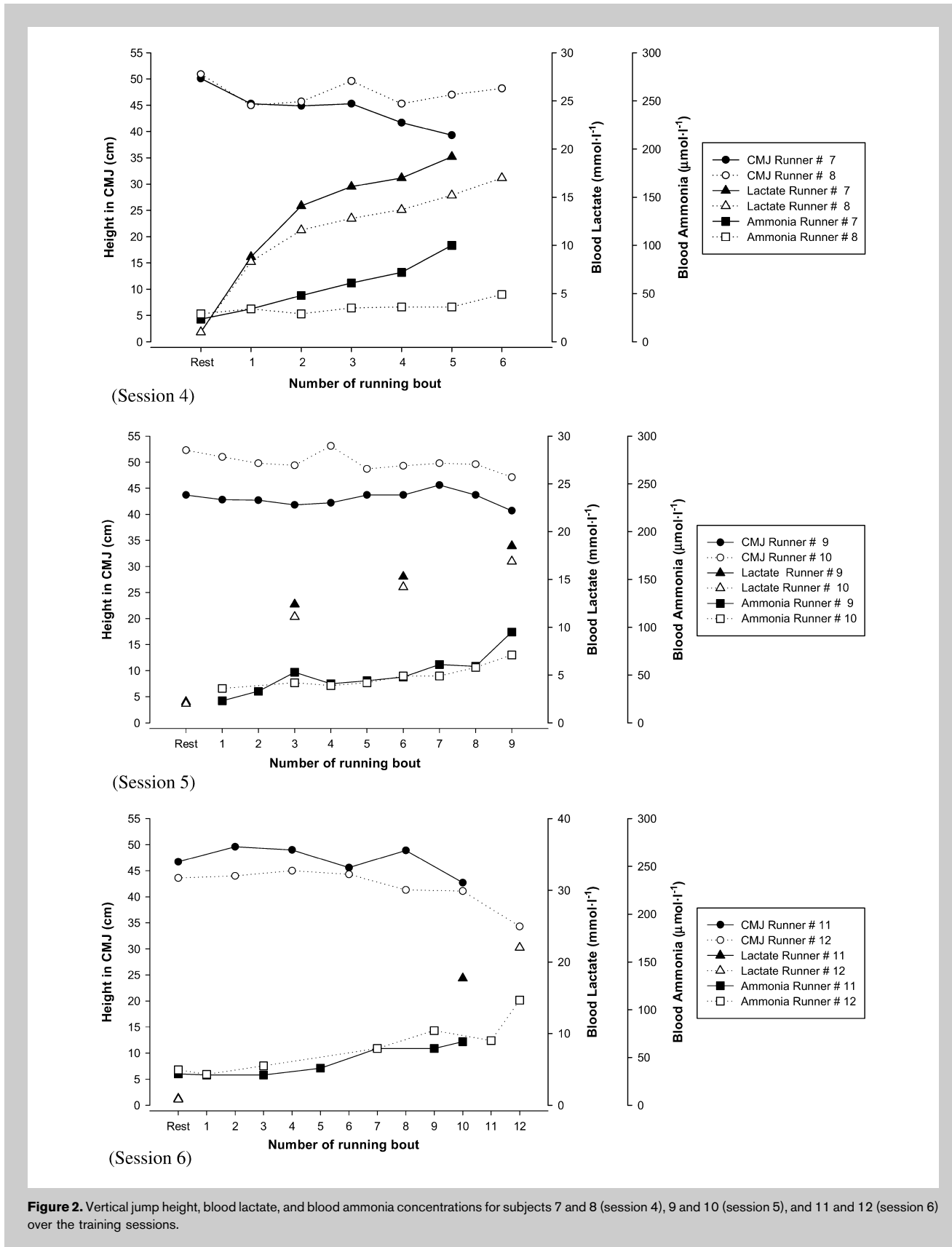


Figure 2. Vertical jump height, blood lactate, and blood ammonia concentrations for subjects 7 and 8 (session 4), 9 and 10 (session 5), and 11 and 12 (session 6) over the training sessions.

Figure 1 shows height in vertical jump and blood lactate and ammonia concentrations during training sessions 1 (Figure 1; session 1), 2 (Figure 1; session 2), and 3 (Figure 1; session 3). Figure 1 (session 1) shows that there was a marked increase in blood lactate concentration in both athletes between the sixth and the last running bout, although the increase was more pronounced in athlete 1 (from 13 to 16 mmol·L⁻¹) than in athlete 2 (from 13.8 to 15 mmol·L⁻¹). From the first running bout, blood ammonia levels progressively increased in athlete 1, reaching values near 75–100 μmol·L⁻¹ during the last running bouts. However, in athlete 2, blood ammonia remained near resting values (≤50 μmol·L⁻¹) throughout the training session. Jumping height remained relatively constant during the first 4–5 running bouts, and they later fell during the remaining work periods. The decline in jumping height was higher in the athlete showing higher initial jumping height values (19%; athlete 1) than in the athlete with lower initial levels (13%; athlete 2).

Training Session 2

Sprint running times during the 6 × 100-m running bouts (11.78 ± 0.15 seconds; range: 11.43–11.99 seconds) were slightly higher than those programmed (11.50 seconds; *p* < 0.01).

Figure 1 (session 2) shows that there was a gradual and parallel increase in blood lactate and ammonia concentrations in both athletes during the training session. At the end of the last running bout analyzed, athlete 3 presented higher blood lactate (15 vs. 13.6 mmol·L⁻¹) and ammonia levels (90 vs. 75 μmol·L⁻¹) than athlete 4. Jumping height remained relatively constant during the first 3–5 running bouts and later fell during the last 4 running bouts in athlete 3 and the last running bout in athlete 4. The decline in jumping height was higher in the athlete showing higher initial jumping height (11%; athlete 3) than in the athlete with lower initial levels (6%; athlete 4).

Training Session 3

Running times during the 8 × 200-m running bouts (25.68 ± 0.52 seconds; range: 24.64–26.66 seconds) were slightly lower than those programmed (26.00 seconds; *p* < 0.05).

Figure 1 (session 3) shows that blood ammonia concentrations presented a similar pattern in both athletes because they remained near resting values during the first 3 running bouts, after which the concentration tended to increase progressively. Blood ammonia and blood lactate concentrations in the athletes after the last running bout were near 100 μmol·L⁻¹ and 19–20 mmol·L⁻¹, respectively. Height in vertical jump remained relatively constant during the first 4 running bouts and later fell during the remaining work periods. It is noteworthy that the decline in jumping height (18%) at the end of the training session was similar in both athletes, who presented similar initial jumping height.

Training Session 4

Running times during the 6 × 300-m running bouts (40.66 ± 0.90 seconds; range: 39.60–42.11 seconds) were similar than those programmed (40.80 seconds). Athlete 7 could only complete 5 of the 6 programmed running bouts because of exhaustion.

Figure 2 shows vertical jumping height and blood lactate and ammonia concentrations during training sessions 4 (Figure 2; session 4), 5 (Figure 2; session 5), and 6 (Figure 2; session 6). Figure 2 (session 4) shows that blood lactate concentration rose sharply during the first 2 running bouts, followed by a more gradual increase. At the end of the exercise, blood lactate values were 19.2 mmol·L⁻¹ (athlete 7) and 17 mmol·L⁻¹ (athlete 8). From the first running bout, blood ammonia levels progressively increased in athlete 7, reaching values around 100 μmol·L⁻¹ during the last running bouts. However, blood ammonia remained near resting values in athlete 8 throughout the training session. Jumping height remained relatively constant during the first 3–4 running bouts and later fell during the remaining work periods.

Training Session 5

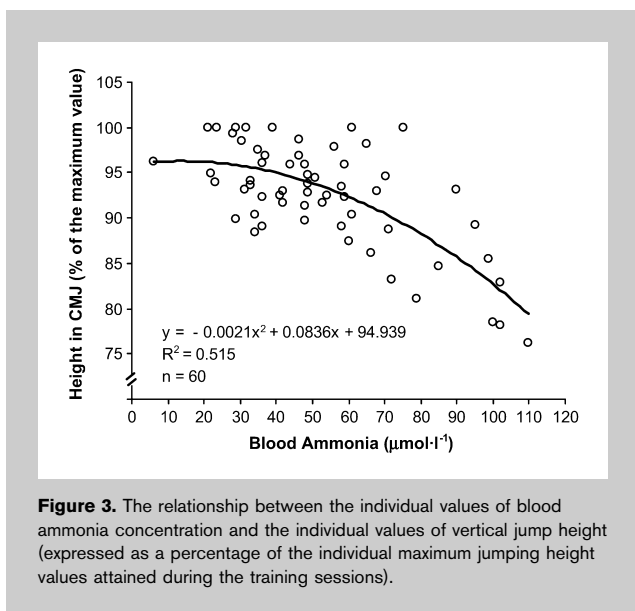
Running times during the 3 × 3 × 300-m running bouts (40.88 ± 0.36 seconds; range: 40.03–41.35 seconds) were similar to the programmed time (40.80 seconds).

Figure 2 (session 5) shows that there was a progressive increase in blood lactate concentration in both athletes between the third and the last running bouts, although the increase was more pronounced in athlete 9 (from 12 to 18.5 mmol·L⁻¹) than in athlete 10 (from 11 to 17 mmol·L⁻¹). Blood ammonia concentration and height in vertical jump remained near resting values until the last 2 running bouts, after which the values tended to progressively increase (ammonia) and decrease (jumping height), respectively. The decline in jumping height was higher in the athlete with higher initial jumping height (10%; athlete 10) than in the athlete with lower initial levels (7%; athlete 9).

Training Session 6

Running times during the 12 × 300-m running bouts (43.11 ± 1.12 seconds; range: 41.80–45.28 seconds) were higher than those programmed (42.50 seconds; *p* < 0.05). Athlete 11 could only complete 11 of the 12 programmed running bouts because of exhaustion.

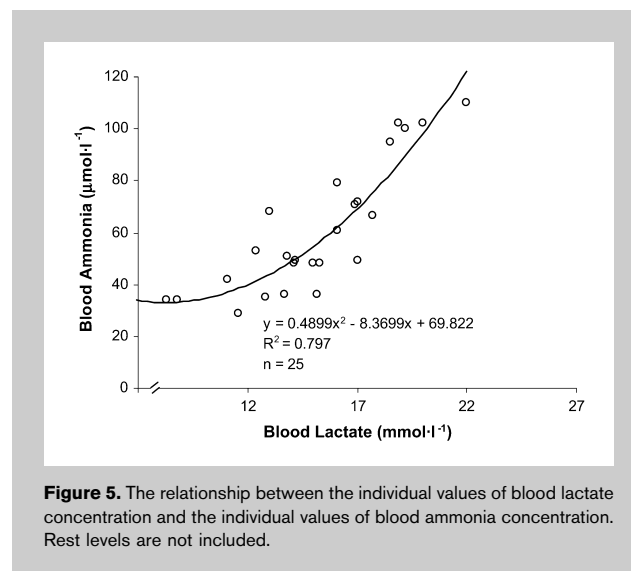
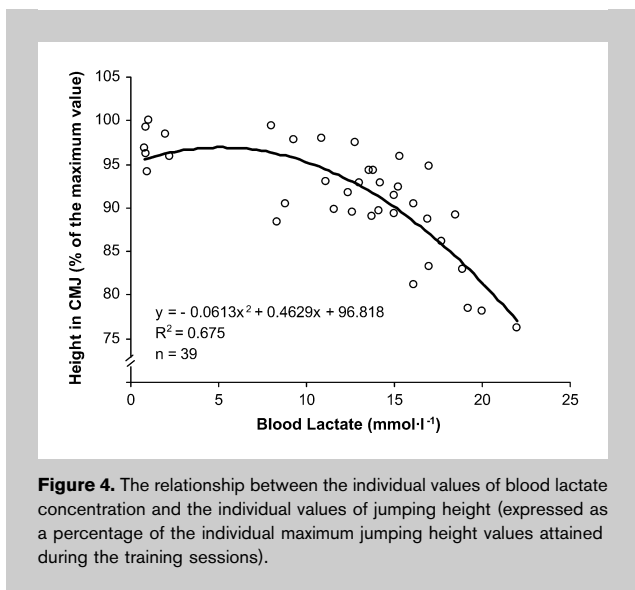
Figure 2 (session 6) shows that at the end of the last running bout (11th and 12th running bout for athlete 11 and 12, respectively), athlete 12 presented higher blood lactate concentrations (22 mmol·L⁻¹) than athlete 11 (18 mmol·L⁻¹). Blood ammonia and jumping height remained near resting values until the fourth (athlete 11) or the fifth (athlete 12) running bouts, after which the values tended to progressively increase (ammonia) and decrease (jumping height), respectively. The fall in jumping height after the last work repetition (11th) done by both athletes was higher in the athlete showing higher initial jumping height (9%; athlete 11) than in the athlete with lower initial levels (5%; athlete 12).



Relationships Among Height in Vertical Jump, Blood Lactate, and Blood Ammonia Concentration

Figure 3 shows the significant ($p < 0.05$; $R^2 = 0.51$) curvilinear negative relationship between individual values of blood ammonia concentration and individual values of jumping height (expressed as a percentage of the individual maximum jumping height attained during the training sessions).

This relationship illustrates that when blood ammonia levels did not exceed the approximate upper limit of the rest reference range (40–50 $\mu\text{mol}\cdot\text{L}^{-1}$), jumping height did not change significantly from maximum values. However, when blood ammonia values approximately exceeded the



upper limit of the rest reference range, the jumping height decreased sharply.

The significant ($p < 0.05$; $R^2 = 0.68$) curvilinear negative relationship between the individual values of blood lactate concentration and the individual values of jumping height (expressed as a percentage of the individual maximum jumping height attained during the training sessions) is showed in Figure 4.

For blood lactate levels not exceeding 8–12 $\text{mmol}\cdot\text{L}^{-1}$, the jumping height did not change significantly from maximum values. However, when blood lactate concentrations approximately exceeded 8–12 $\text{mmol}\cdot\text{L}^{-1}$, the jumping height decreased sharply. The data are consistent with a sharp decrease in jumping height when whole blood lactate levels exceed approximately 8–12 $\text{mmol}\cdot\text{L}^{-1}$.

Figure 5 shows the curvilinear significant ($p < 0.05$; $R^2 = 0.80$) positive relationship between individual values of blood lactate concentration and individual values of blood ammonia.

This relationship illustrates that blood ammonia levels did not change significantly from the upper limit of the rest reference range (40–50 $\mu\text{mol}\cdot\text{L}^{-1}$) for blood lactate concentrations not exceeding approximately 8–12 $\text{mmol}\cdot\text{L}^{-1}$. However, when blood lactate concentrations approximately exceeded the level of 8–12 $\text{mmol}\cdot\text{L}^{-1}$, a sharp increase in blood ammonia levels above the rest reference range was observed.

DISCUSSION

To our knowledge, this is the first study describing metabolic and neuromuscular performance characteristics of several typical training sessions in a group of elite 400-m running athletes. The present results show that, although the high-intensity intermittent training sessions programmed were very diverse in principle, their physiological responses were

nevertheless quite similar because a similar pattern of high blood lactate ($14\text{--}23\text{ mmol}\cdot\text{L}^{-1}$) and ammonia levels ($50\text{--}100\text{ }\mu\text{mol}\cdot\text{L}^{-1}$) was observed at the end of all the training sessions. These extremely high levels of blood lactate have also been found in 400-m runners during high-intensity treadmill running sessions (23) or after official competitions (19) and have been associated with increased muscle lactate production (3,7,12,20) with large reductions in muscle glycogen (12,26), particularly in type IIx fibers (7), whereas blood and muscle pH can reach values as low as 7.0 (20) and 6.0 (3), respectively. This suggests that anaerobic glycogenolysis is extensively activated during these types of exercises, preferentially in type IIx muscle fibers (12). The training sessions analyzed in the present study may be considered as specific types of training because they allow the successful reproduction of the physiological responses observed during official 400-m running competitions in elite athletes (19).

The appearance of high blood ammonia levels during these types of high-intensity intermittent exercises is primarily considered as an effect of accelerated ammonia formation in muscle associated with the very specific role that phosphagens play during this type of exercise (17,31). Thus, the metabolic demand of such types of intermittent exercise requires a high skeletal muscle ATP turnover that usually results in large reductions in muscle PCr concentrations (3,7,12,20) and in the muscles' ability to match the rate of ATP supply with its rate of utilization, thereby causing a marked reduction of skeletal muscle ATP content (4,17,31), particularly in type IIx fibers (7). This fall in muscle ATP content is closely linked to an increase in muscle adenosine monophosphate (AMP) levels (17,31), its deamination by AMP deaminase, and a corresponding increase of muscle inosine monophosphate (IMP) levels and muscle and blood ammonia concentrations (17,31), resulting in an accelerated purine nucleotide degradation and a loss of total adenine nucleotides from the muscle (14). Therefore, it can be suggested that the high blood ammonia levels observed during the high-intensity intermittent exercises analyzed in this study may represent an extracellular marker of pronounced muscle ammonia production and its net diffusion in the blood, associated to a decline in muscle adenine nucleotide stores, mainly by a pronounced reduction in muscle ATP content (17,31).

A significant relationship was observed in the present study between individual levels of blood lactate and individual levels of blood ammonia (Figure 5). The curvilinear fashion of the curve reveals that blood ammonia remained near resting levels for blood lactate levels lower than $8\text{--}12\text{ mmol}\cdot\text{L}^{-1}$, but when blood lactate concentration exceeded $8\text{--}12\text{ mmol}\cdot\text{L}^{-1}$, blood ammonia levels increased abruptly from rest values compared with blood lactate concentrations. A threshold of a sharp upward break point in blood ammonia accumulation corresponding to whole blood lactate levels of approximately $12\text{ mmol}\cdot\text{L}^{-1}$ or to plasma lactate levels of $14\text{ mmol}\cdot\text{L}^{-1}$ has been observed in recreationally active subjects (28) and in

low-level 400-m runners (27). This finding is compatible with some reports in humans (14), showing that muscle ammonia and H^+ accumulation and release in blood during high-intensity exercise does not begin until high muscle and blood lactate levels are reached and muscle pH is below a certain level. The significant relationship observed between blood lactate and blood ammonia levels in the present study allows for elite 400-m runner coaches to indirectly estimate the magnitude of degree of blood ammonia accumulation during high-intensity intermittent exercises from blood lactate concentration values.

In the majority of the training sessions analyzed, the 400-m runners who showed the greatest initial vertical height values during vertical jump tended to have the largest decreases in vertical height values with successive sprints. This is in line with previous investigations performed with track and field jumpers (5) and national level sprint runners (24), where individuals with high initial performance of short duration, such as vertical jump (5,24) or peak power output during cycloergometer sprints (3), demonstrated greater susceptibility to fatigue (5,24) during high-intensity exercise than individuals with lower performance of short duration. This greater susceptibility to fatigue has been associated with a higher proportion of fast twitch (FT) fibers (5), lower capillary density (18), oxidative enzyme content (18), and endurance fitness status (3). From a practical point of view, this suggests that 400-m athletes with higher initial vertical jump performances have more rapid muscle contraction failure and recover more slowly because their muscles are probably made up of a high proportion of FT muscle fibers. Therefore, 400-m runners with higher initial vertical jump performances should rest for longer between-exercise bouts during high-intensity training sessions than athletes with lower initial vertical jump performances, to maintain the same relative capability of leg extensor muscles to generate more mechanical power throughout the training session. The large variation in vertical jump profiles observed among the 400-m runners stresses the importance of following an individualized modeling approach to monitor training sessions in elite athletes who are homogeneous in performance.

A common picture during the training sessions analyzed was that vertical jumping performance was maintained during the initial exercise bouts up to a point of further increase in the number of exercise bouts, caused a pronounced loss in vertical jumping performance. In addition, significant negative curvilinear relationships were found between the individual values of vertical jump performance (as a percentage of the individual maximum values) and individual values of blood ammonia, as well as individual values of blood lactate concentrations (Figures 3 and 4). It indicates that force generating capacity during vertical jump performance began to decrease sharply when blood ammonia concentrations approximately exceed physiological rest values ($45\text{--}50\text{ }\mu\text{mol}\cdot\text{L}^{-1}$) or when blood lactate concentrations exceed

8–12 mmol·L⁻¹. Associations between vertical jump performance and blood lactate concentrations have also been found in lower level 400-m runners performing single sprints from 100 to 400 m, with rest periods of 5–24 hours between the runs, at the velocity of the 400 m (22). The observed relationship between decreases in vertical jump performance and increases in blood ammonia concentrations above rest values (an indirect marker of reduced skeletal ATP content (17,31)) support previous findings (1,2), which suggests that decreased availability of ATP or PCr levels or both in a substantial fraction of the fast or twitch high-glycolytic fibers may be a significant contribution factor of fatigue.

Although the concentrations of intramuscular ATP or PCr stores were not directly measured in this study, the relationships observed among blood ammonia, blood lactate concentration, and vertical jumping performance allow us to differentiate 2 main exercise modes in each of the studied training sessions, in terms of energy status. (a) The first exercise bout characterized by blood ammonia concentrations and vertical jumping performance not changing from physiological resting levels, while blood lactate levels do not exceed 8–12 mmol·L⁻¹. Previous studies have shown that the energy status is maintained in this metabolic situation because muscular PCr levels fall by less than 60–70% (25,26), muscle ATP levels and adenine nucleotide pool values do not change (2,25,26), and maximal running velocity is maintained (1,2). (b) When the number of repetition bouts is increased, there is a given critical number of repetitions beyond which an increase in blood ammonia concentrations above rest values and a continuous increase in blood lactate that may reach values up to 13–30 mmol·L⁻¹ at the end occur, although vertical jumping performance is progressively decreased. In this metabolic situation, exercise has been associated with signs of energetic deficiency and delayed functional recovery because muscle PCr stores are almost completely broken down (3,25,26), leading to a significant decrease in muscle ATP levels (20,26) and adenine nucleotide pool, particularly in type II fibers (7,25), whereas maximal running velocity is decreased (1,2,25). The practical application for an efficient control of training loads is that the measurement of vertical jumping performance could be used during high-intensity intermittent training sessions to indirectly estimate the functional state of the muscle contractile machinery associated with the ability to regenerate ATP at high rates.

As mentioned in the Introduction, 2 main different modes of high-intensity intermittent training sessions (leading either to medium or to high blood lactate levels) can be differentiated in terms of energy status. However, the fact is that the great majority of the usual training sessions programmed into the training schedule of 400-m elite athletes during the precompetition or competition phase usually lead to extremely high blood lactate and ammonia levels and decreased force generating capacity. These types of training

sessions are very popular among athletes and coaches and are recommended mainly on the basis of subjective observations and experience in the field. The reason why 400-m running coaches conduct little, if any, high-intensity intermittent training sessions leading to middle-range blood lactate levels (8–12 mmol·L⁻¹ or lower) is unknown. Few studies have examined the effects of intermittent training leading to blood lactate values stabilized around 8–12 mmol·L⁻¹ on anaerobic performance (9,11,16,21,32). These studies have found, in physically active or endurance-trained subjects, that after training 3–4 times a week for 6–8 weeks, significant increases were observed in maximal voluntary strength of the knee extensor muscles (32), vertical jump (32), running sprint performance (9,16,21,32), buffer capacity (11), monocarboxylate transporter 1 (21), and the activity of high energy phosphate transferring enzymes (32), whereas the percentage of type II fibers (9,32) or the total amount of muscle phosphagen (9,16,32) was also increased or unchanged. Taking into consideration these positive effects observed on anaerobic performance, it is conceivable that increasing the frequency of this type of training with lower metabolic stress and decreasing the frequency of the traditional training leading to extremely high blood lactate levels should allow athletes to practice at competitive intensity of exercise for more frequent training sessions with lower fatigue. This lower fatigue should play a role in preventing or avoiding negative effects (e.g., increased generation of free radicals and cell necrosis (29), muscle protein wasting (8), increased type I muscle fiber percentage (10), unchanged buffering capacity (13) and performance (10), muscle purine loss from muscle exceeding the rate of purine salvage (12), and decreased resting levels of skeletal muscle adenine nucleotides (13,31)) observed after traditional training with extremely high anaerobic lactacid demands, when this type of training is repeated too frequently.

In conclusion, high blood lactate (14–23 mmol·L⁻¹) and ammonia levels (50–100 μmol·L⁻¹) were observed during 6 habitual high-intensity intermittent training sessions of varying duration and intensity performed by elite male 400-m athletes. Vertical jumping performance was maintained during the initial exercise bouts up to a point of further increase in the number of exercise bouts, caused a pronounced decrease in vertical jumping performance, particularly in subjects with the highest initial vertical jump. The relationships observed among blood ammonia, blood lactate, and vertical jumping performance suggest that vertical jumping performance approximately begins to decrease when blood lactate concentration exceeds 8–12 mmol·L⁻¹ and blood ammonia levels increase abruptly from rest values. The decrease in vertical jumping performance may indirectly reflect a state of energy deficit of the muscle contractile machinery associated with the inability to regenerate ATP at high rates. Further studies are required to accurately determine the most efficient combination in an annual program of training sessions with and without signs of energy deficit

resulting in the greatest improvement in 400-m running performance.

PRACTICAL APPLICATIONS

This study has practical importance in that it shows that (a) the high-intensity intermittent training sessions performed regularly by elite 400-m runners may be considered as specific types of training because they allow the successful reproduction of the physiological responses observed during official 400-m running competitions in elite athletes; (b) the significant relationship observed between blood lactate and blood ammonia levels in the present study allows for elite 400-m runner coaches to indirectly estimate the magnitude of degree of blood ammonia accumulation during high-intensity intermittent exercises from blood lactate concentration values; (c) 400-m runners with higher initial vertical jump performances should rest for longer between-exercise bouts during high-intensity training sessions than athletes with lower initial vertical jump performances, to maintain the same relative capability of leg extensor muscles to generate more mechanical power throughout the training session; (d) the measurement of vertical jumping performance could be used during high-intensity intermittent training sessions to indirectly estimate the functional state of the muscle contractile machinery associated with the ability to regenerate ATP at high rates; and (e) it is conceivable that increasing the frequency of high-intensity intermittent training sessions, leading either to medium blood lactate levels (lower than 8–12 mmol·L⁻¹) and blood ammonia concentrations or vertical jumping performance not changing from physiological basal levels, and decreasing the frequency of the traditional training, leading to extremely high blood lactate levels, should allow athletes to practice at competitive intensity of exercise for more frequent training sessions with lower fatigue.

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