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Physical performance and metabolic changes induced by combined prolonged exercise and different energy intakes in humans

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Abstract. The purpose of this study was to evaluate the effects on physical performance of three levels of energy intake during a 5-day period of prolonged physical exercise and relative sleep deprivation. A group of 27 male soldiers were randomly assigned to three groups receiving either 1800 kcal$\cdot$24 h^{-1} (7560 kJ, LC), 3200 kcal$\cdot$24 h^{-1} (13440 kJ, MC) or 4200 kcal$\cdot$24 h^{-1} (17640 kJ, HC). They took part in a 5-day combat course (CC) of heavy and continuous physical activities, with less than 4 h sleep per day. Performance capacity was tested just before and at the end of CC. Maximal oxygen uptake ($\dot{V}O_{2\max}$) was determined during an exhausting incremental exercise test on a cycle ergometer. Anaerobic performance was measured from the time during which exercise could be maintained at supra maximal loads on a cycle ergometer. After CC, the subjects receiving LC exhibited a 14% decrease in power output at exhaustion in the incremental exercise test [from 325 (SEM 8) to 278 (SEM 9) W, $P<0.001$] and a significant decrease in $\dot{V}O_{2\max}$ of 8% [from 3.74 (SEM 0.06) to 3.45 (SEM 0.05) l$\cdot$min^{-1}, $P<0.05$]. The remaining two experimental groups demonstrated the same mechanical and metabolic performances on days 1 and 5. Anaerobic performance was not influenced by energy intake and the field course. Blood samples were obtained at rest on days 1 and 5. At the end of CC, the data demonstrated a significant decrease in blood glucose concentrated ion ($P<0.01$) for LC diet only. Plasma free fatty acid, blood glycerol and β-OH butyrate were significantly increased in all groups, from day 1, but the values observed for LC were higher than those for the MC and HC diets. The concentrations of the anabolic hormones, insulin and testosterone, decreased in the three groups, the lowest values being observed in the LG group ($P<0.05$). In conclusion, we found that only a severe energy deficit decreased physical performance during submaximal exercise. A moderate deficit between energy intake and expenditure did not affect performance. Supramaximal exercise did not appear to be influenced by energy intake and CC.

Key words: Diet – Prolonged exercise – Physical performance – Metabolism – Undereating

Introduction

Several kinds of prolonged physical exercise such as hiking, mountain climbing and military manoeuvres induce a negative energy balance due to smaller energy intake than expenditure. The influence of fasting on metabolic changes and physical performance have been studied extensively (Dohm et al. 1986; Gleeson et al. 1988; Knapik et al. 1987; Loy et al. 1986), and it appears that short-term fasting (1–3 days) reduces physical performance and modifies the metabolic response to exercise. Liver glycogen has been shown to be rapidly depleted as starvation extends beyond 18–24 h (Hultman and Nilson 1971) and, by the process of lipolysis, the most abundant fuel supply in the form of body fat becomes available to the fasted individual during prolonged submaximal exercise. This decrease in muscle and liver glycogen stores and hypoglycaemia seem to be the cause of fatigue (Loy et al. 1986). The onset of fatigue resulting from the combination of low energy intake and increased energy expenditure has rarely been investigated. The purpose of the present study was therefore to determine what energy intake corresponds to a decrease in performance. Three energy intakes were studied during 5 days of increased energy expenditure. The experiment was conducted during a combat course which was part of French Army commando training. The standard light weight diet of 3200 kcal$\cdot$24 h^{-1} (13440 kJ$\cdot$24 h^{-1}) served as the basis, and was either reduced to 1800 kcal$\cdot$24 h^{-1} (7560 kJ$\cdot$24 h^{-1}) or increased to 4200 kcal$\cdot$24 h^{-1} (13640 kJ$\cdot$24 h^{-1}).

Changes in aerobic and anaerobic capacities, resting metabolism and hormonal concentrations are de-

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scribed after 5 days of exercise consuming low and high energy diets.

Methods

Subjects. A group of 27 special operation male soldiers took part in this study. They gave their voluntary written consent to participate in this investigation after being informed of the purpose, procedures and risks of the study, in accordance with French Army regulations. The study was conducted during a combat course which was part of their normal training.

Combat course. The combat course took place at the National Centre for commando training in Montlouis in the Pyrenees mountains, over a period of 96 h, from 6 a.m. on day 1 until 6 a.m. on day 5. The subjects walked distances of 25–35 km at night, across the countryside, avoiding roads, lanes and trails. They were carrying backpacks of 11 (SEM 1.2) kg.

During the combat course the total uphill and downhill walking distance was 2800 m. Several parts of the course involved mountain climbing. In addition to walking, the subjects took part in frequent simulated combat activities. The continuous activity allowed only a few periods of sleep amounting to 3–4 h every 24 h. All the subjects trained as one group. The course took place in June with temperatures ranging between 18° C and 25° C.

Diet. The subjects were randomly assigned to one of three groups ($n=9$) differing according to the energy content of their diet. The basis for the three diets was the light weight commando ration. One group identified as medium energy diet (MC) received the complete ration with a mean energy content of 3200 $\text{kcal}\cdot 24\ \text{h}^{-1}$ (13440 $\text{kJ}\cdot 24\ \text{h}^{-1}$). This ration of a mean mass of 900 g consisted of two freeze dried meals (Lyofal, France) of 480 kcal (2016 kJ) each, 1200 kcal (5040 kJ) of bread in the form of biscuit and 1000 kcal (4200 kJ) of energy bars, chocolate, and candied fruit. The percentage of each class of nutrient in the total energy supplied was 55% carbohydrates, 30% lipids, 15% proteins.

The group identified as low energy diet (LC) received only 1800 $\text{kcal}\cdot 24\ \text{h}^{-1}$ (7560 $\text{kJ}\cdot 24\ \text{h}^{-1}$) obtained by removing the bread and candied fruits. The percentage of each class of nutrient was 47% carbohydrates, 35% lipids and 18% proteins.

The last group identified as high energy diet (HC) received 4200 $\text{kcal}\cdot 24\ \text{h}^{-1}$ (17640 $\text{kJ}\cdot 24\ \text{h}^{-1}$) by adding 1000 kcal (4200 kJ) of energy bars to the commando ration. The composition was 60% carbohydrates, 25% lipids, 15% proteins. The rations were consumed during three main meals, only energy bars were eaten ad libitum.

Exercise test. The day before the course the subjects were tested for their aerobic and anaerobic capacities. Two systems of gas analysers and ergometers were used simultaneously for maximal aerobic power and maximal oxygen uptake determinations in order to test all the men between 9 a.m. and 3 p.m. The two gas analysers were open circuit automatized systems (Horizon, Sensors Medics, USA); the cycle ergometers were mechanically braked (Ergomeca, Toulon, France). The maximal aerobic capacity was measured during an incremental exercise test. After 3 min of warming up at 125 W the intensity was increased by 25 W every minute until exhaustion. To test the subjects in the same nutritional state, the first group was tested between 9 a.m. and noon after having eaten a standard breakfast at 8 a.m. The second group was tested between noon and 3 p.m. after receiving the same equal energy diet at 9 a.m. and at 11 a.m.

The subjects were tested in random order. The anaerobic performance was evaluated with a simplified test derived from the method validated by Brue et al. (1981). A mechanically braked ergometer (Ergomeca) was used with an electronic system to measure and display the number of pedal revolutions per minute (rpm). An initial pedalling rate of 120 rpm without load was required from the subject, and a 6 kg load was suddenly added. The time elapsed until the pedalling rate was reduced from 120 rpm to 100 rpm was used as a measure of anaerobic performance. The anaerobic test was performed after a short recovery time of 1 h after the aerobic determination.

The subjects were weighed on day 1 and on day 5 before breakfast.

Blood parameters. After an overnight fast, venous blood was sampled from an antecubital vein after 15-min rest in a lying position on days 1 and 5. A sample of 20-ml blood was collected in heparinized syringe and centrifuged at 4° C. Plasma was stored at −80° C and used for subsequent determinations. Glucose, lactate, glycerol and β-OH butyrate concentrations were assayed by enzymatic methods (Bergmeyer 1963). Free fatty acids (FFA) concentrations were measured using a commercially available kit (Nefa C test Wako Biolyon, France), and myoglobin concentration was evaluated by a radio-immunological method using a commercial kit (Myok CIS, France). Testosterone and insulin concentrations were assayed by radio-immunological methods using commercial kits (SB Testo and Insik-CIS, France). The analytical sensitivity of the minimal detectable testosterone concentration was 0.01 $\text{ng}\cdot\text{ml}^{-1}$ and the precisions in terms of within-assay and between-assay coefficients of variation were 6% and 8%, respectively. The analytical sensitivity for insulin was 0.1 $\text{mIU}\cdot\text{ml}^{-1}$ and the precisions in terms of intra-assays and inter-assays were 5% and 6%, respectively.

Statistics. Data were examined using a two-way analysis of variance ANOVA with repeated measures. A paired Student's t-test was used to identify specific differences when a significant difference was observed with ANOVA. The significance level was chosen at $P<0.05$.

Results

Aerobic performance

Power output at exhaustion (Fig. 1) was significantly decreased ($P<0.01$) from 325 (SEM 8) W to 278 (SEM 9) W in the LC group.

The ANOVA indicated a significant effect of the combat course on maximal oxygen uptake ($F^2_{25}=6.10$,

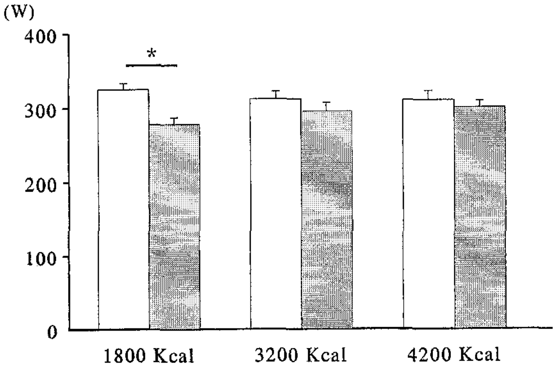

Fig. 1. Power output at exhaustion during an incremental maximal exercise test measured on cycle ergometer before and after a combat course performed with three energy intakes: 1800, 3200 or 4200 $\text{kcal}\cdot 24\ \text{h}^{-1}$ (7560, 13440 and 17640 $\text{kJ}\cdot 24\ ^{-1}$, respectively). □ Before; ▨ after. * Indicates that results differ before and after the combat course ($P<0.01$)

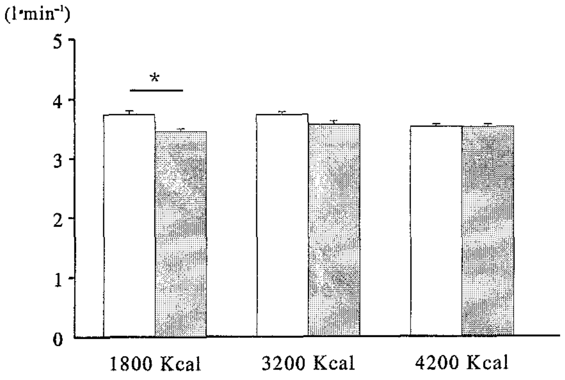

Fig. 2. Maximal oxygen uptake during a maximal exercise test measured on a cycle ergometer before and after a combat course performed with three levels of energy intake: 1800, 3200 or 4200 kcal·24 h^{-1} (7560, 13440 and 17640 kJ·24 h^{-1}, respectively). □ Before; ▨ after

$P<0.05$) and an effect resulting from the diet ($F^2_{25}=4.22$, $P<0.05$). The comparison for each ration shows that the maximal oxygen uptake (Fig. 2) was reduced by 8% in the LC group [3.74 (SEM 0.06) l·min^{-1} before the combat course vs 3.45 (SEM 0.05) l·min^{-1} after the combat course, $P<0.05$]. The mean oxygen uptakes during submaximal exercise were not different among situations or diets. The ANOVA showed that the respiratory exchange ratio (R) was significantly reduced by the combat course from rest to the second step of incremental exercise ($F^2_{25}=4.32$, $P<0.05$) without differences among diets (Fig. 3).

Body mass

The LC group showed the largest decrease in body mass with a mean loss of 2.9 (SEM 0.7) kg, the MC group lost 1.9 (SEM 1.1) kg while the HC group only lost 1.5 (SEM 0.8) kg.

Anaerobic performance

Figure 4 gives the data of the anaerobic power estimations performed. The time of exercise for a supra maximal load was the same among diets, before and after the combat course.

Resting blood metabolites

Blood glucose concentration was only significantly decreased by the combat course in the LC group ($P<0.01$), whereas the values observed in the other group did not differ for any sampling time. Glycerol concentration was significantly increased in all groups and the values observed at the end of the combat course in the LC group were significantly higher ($P<0.05$) than those measured in the other groups on day 5. The β-OH butyrate concentration was increased in all three groups. The highest increase was observed in the LC group (five or sixfold).

Plasma FFA concentration on day 5 was approximately four times higher in the LC group than the corresponding value observed before the course. There was only a twofold increase in plasma FFA concentration in the MC and the HC groups. Myoglobin concentration exhibited the same increase at the end of the combat course for all three groups (Table 1).

Plasma hormones

Plasma insulin concentration was significantly decreased by the combat course in all groups. But the most obvious decrease, 60% from initial value, was observed in the LC group ($P<0.01$). Plasma testosterone concentration was decreased by 50% in the LC group ($P<0.01$), by 20% in the MC group, and by 23% in the HC group on day 5, compared to values measured before the course ($P<0.05$) (Table 2).

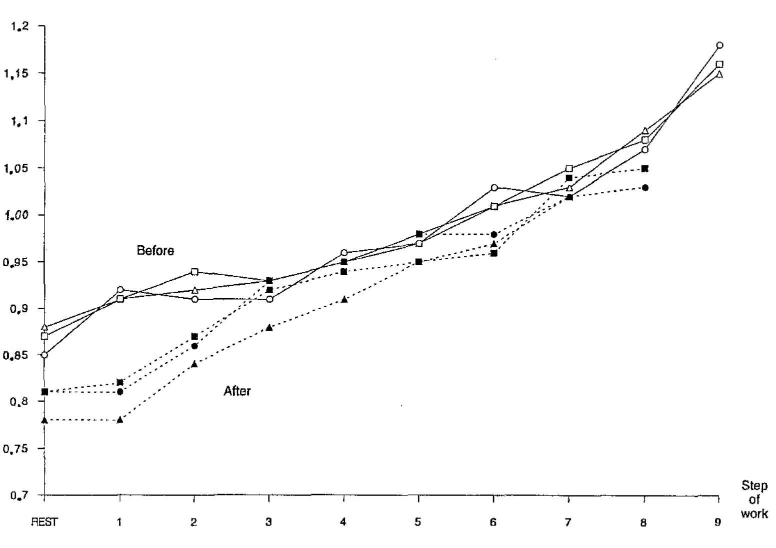

Fig. 3. Respiratory exchange ratio curves measured during a progressive maximal exercise test from rest to exhaustion. Before the combat course: □, high energy diet group; △, medium energy diet group; ●, low energy diet group. After the combat course: ■, high energy diet group; ▲, medium energy diet group; ●, low energy diet group

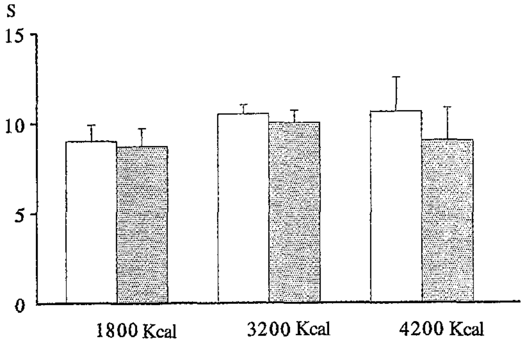

Fig. 4. Anaerobic power measured, before and after a combat course performed with three energy intakes: 1800, 3200 or 4200 kcal·24 h^{-1} (7560, 13440 and 17640 kJ·24 h^{-1}, respectively). □ Before; ▨ after

Table 1. Blood metabolite concentrations measured before (B) and after (A) a combat course performed with a low energy intake (LC), a medium energy intake (MC) and a high energy intake (HC)

Diet		LC		MC		HC	
kcal·24 h^{-1}		1800		3200		4200	
		Mean	SEM	Mean	SEM	Mean	SEM
Glucose	B	5.2	0.2	5.1	0.3	5.1	0.2
(mmol·l^{-1})	A	4.1	0.3**	4.8	0.2	5	0.3
Glycerol	A	21	5	23	4	19	3
(μmol·l^{-1})	B	100	15**	61	12*	55	2*
β-OH Butyrate	B	50	15	32	11	35	27
(μmol·l^{-1})	A	280	55**	88	27*	74	22
FFA	B	0.27	0.01	0.23	0.03	0.22	0.02
(mmol·l^{-1})	A	1.12	0.2**	0.48	0.12*	0.51	0.14
Myoglobin	B	52	7	56	9	48	12
(ng·ml^{-1})	A	151	15*	147	12*	162	10*

FFA, Free fatty acids. Significantly different from B values
* $P<0.05$, ** $P<0.01$

Table 2. Blood hormone concentrations measured before (B) and after (A) a combat course performed with a low energy intake (LC), a medium energy intake (MC) and a high energy intake (HC)

Diet		LC		MC		HC	
kcal·24 h^{-1}		1800		3200		4200	
		Mean	SEM	Mean	SEM	Mean	SEM
Insulin	B	13.32	0.25	12.8	0.30	15.2	0.28
IU·ml^{-1}	A	5	0.12**	9	0.17*	12.5	0.16*
Testosterone	A	6.3	0.9	6.2	0.9	5.9	0.2
ng·ml^{-1}	B	3.1	0.4**	4.9	0.5*	4.5	0.3*

Significantly different from B values
* $P<0.05$, ** $P<0.01$

Discussion

Levels of energy expenditure

Previous data obtained during the same field conditions have shown that 5 days of intense military activities induced an energy requirement estimated to be between 8000 and 10000 kcal·24 h^{-1} (33600–42000 kJ·24 h^{-1}). More recently, the doubly labelled water method has been used to determine 24-h energy expenditure during military field training; 10 h of rest, 8 h of very light military activities, and 6 h of heavy military activities have been found to require an energy expenditure of 4700 kcal (19740 kJ, Delany et al. 1989). These different data have shown that energy expenditure during heavy military manoeuvres range between 5000 and 10000 kcal·24 h^{-1} (21000–42000 kJ·24 h^{-1}). The combat course studied here is more similar to the conditions studied by Opstad and Aakvag (1981), and thus the energy expenditure could therefore be estimated to exceed 5000 kcal·24 h^{-1} (21000 kJ·24 h^{-1}).

Effect on physical performance

The main result of the present study was that work capacity and maximal oxygen uptake were decreased during exhausting incremental exercise and that supramaximal exercise performance was not affected by a low energy diet consumed during 5 days of participation in a combat course. The comparison between the three levels of energy supply and the estimated energy expenditure indicated that exercise capacity only decreased as a result of a severe energy deficit. A smaller deficit in energy balance, observed with HC and MC diets did not affect physical performance. In contrast to aerobic capacity, the preservation of anaerobic performance in the LC group confirmed previous results which have shown that a short period of undernutrition or prolonged exercise, inducing a decrease in muscle and liver glycogen stores and resulting in reduced carbohydrate availability, does not impair anaerobic performance (Knapik et al. 1987; Symons and Jacobs 1989). The possible mechanisms involved in the decrease of aerobic performance with LC diet could be related to the biochemical changes such as reduced blood glucose availability and greater use of fat substrates resulting from prolonged exercise with reduced food intake.

The observed elevation in circulating fat metabolites at the end of the combat course confirmed the findings that prolonged exercise repeated on several consecutive days has enhanced lipolysis (Greenhaff et al. 1987; Opstad and Aakvag 1981; Rognum et al. 1981). The decrease in resting and exercising *R* after the combat course indicated enhanced fat participation in energy metabolism. The LC diet stimulated lipid availability. It has previously been shown that several days of continuous simulated combat exercises and reduced food intake has enhanced fat metabolism and decreased mechanical efficiency (Bahr et al. 1991). The exact mechanisms responsible for a decrease in mechanical efficiency with high concentrations of plasma FFA remain obscure.

It could also be suggested that the decrease in power output at exhaustion observed in the LC group resulted from reduced carbohydrate stores. Several studies using a combination of diet and endurance exercise have established a relationship between the decrease in glycogen stores and physical performance (Bergstrom et al. 1967; Hultman 1967). More recently, Walberg et al. (1988) have shown that a low energy diet with low carbohydrate content reduced muscle endurance. It has been suggested that fatigue seems to be caused by the consequences of tissue glycogen depletion or hypoglycaemia (Loy et al. 1986).

Conversely, the performance of short-term supramaximal exercise was not affected by the conditions studied here. It has previously been observed that 5 days of prolonged exercise conserve the capacity for muscle maximal contraction when the endurance time of muscle contraction at 50% of maximal power is reduced (Bigard et al. 1993). These data agree with the findings of Symons and Jacobs (1989) who have shown that high intensity exercise performance is not impaired by low intramuscular glycogen. It is suggested that glycogen stores have no effect upon short-term maximal exercise, because high energy phosphate is always available for immediate anaerobic utilization.

Apart from the energy supply, there was a considerably different carbohydrate intake among the three diets studied here. The LC group received only about 846 $\mathrm{kcal \cdot 24\ h^{-1}}$ (3553 $\mathrm{kJ \cdot 24\ h^{-1}}$) in the form of carbohydrates, while MC and HC diets provided 1760 $\mathrm{kcal \cdot 24\ h^{-1}}$ (7392 $\mathrm{kJ \cdot 24\ h^{-1}}$) and 2520 $\mathrm{kcal \cdot 24\ h^{-1}}$ (10584 $\mathrm{kJ \cdot 24\ h^{-1}}$) of carbohydrates, respectively. The decrease in maximal aerobic capacity observed in the LC group could have been the result of a progressive glycogen depletion. Premature muscle fatigue during the incremental test could have impeded the completion of the last step and consequently diminished maximal oxygen consumption. Blood glucose decreased slightly after the combat course with the LC diet but not enough to induce clinical symptoms of hypoglycaemia. Blood glucose concentration has been shown to decrease during prolonged exercise with low energy intake in humans (Marniemi et al. 1984). However, others have not observed changes in blood glucose concentration in response to prolonged walking in fasted men (Greenhaff et al. 1987).

The hormone changes observed here would seem to confirm previous data that have been obtained under similar conditions (Aakvag et al. 1978; Marniemi et al. 1984). We have found that the decrease in anabolic hormones is influenced both by prolonged exercise and fasting (Guezennec et al. 1982, 1984a). The LC group therefore presented the lowest blood insulin and testosterone concentrations after the combat course. The decrease in plasma insulin concentration enhanced lipid availability. It has been shown that glucose feeding before exercise increases plasma insulin concentration and reduces FFA production (Satabin et al. 1987). A high carbohydrate diet given during 4 days of consecutive walking has been found to maintain the higher plasma insulin concentrations associated with a smaller FFA concentration increase (Maughan et al. 1987). As has been previously observed under similar conditions, plasma testosterone concentration was decreased by several days of prolonged exercise (Aakvag et al. 1978; Marniemi et al. 1984). We have shown that low energy intake enhances a decrease in testosterone concentration and would seem to confirm that the mechanism responsible for this hormone change is related to the energy deficit as has been previously observed in the rat (Guezennec et al. 1982, 1984a). The low concentrations of anabolic hormones observed here, such as testosterone and insulin, could be factors inducing fatigue through their action on protein metabolism. It has been shown that several consecutive days of prolonged exercise enhance protein degradation and amino acid oxidation as substrate (Dohm et al. 1987; Bigard et al. 1993). We have shown that a low testosterone concentration reinforces amino acid availability (Guezennec et al. 1984b). It has been suggested that this increase in amino acid exchange and its consequences on plasma amino acid concentrations could have an effect on central fatigue through the amino acid metabolism (Chaouloff et al. 1985; Parry Billing et al. 1992).

Under the conditions in this study, the association between the LC diet and prolonged exercise depressed anabolic hormones and could have influenced the central cause of fatigue.

In conclusion, the present experiment confirmed that 5 days of severe physical stress combined with different levels of food restriction and sleep deprivation enhanced FFA mobilization, power output at exhaustion and reduced the blood anabolic hormone concentrations.

Our results showed that work production during incremental exercise only decreased when the energy deficit exceeded 3000 $\mathrm{kcal \cdot 24\ h^{-1}}$ (12600 $\mathrm{kJ \cdot 24\ h^{-1}}$). During this period of daily energy expenditure between 5000 and 8000 $\mathrm{kcal \cdot 24\ h^{-1}}$ (21000–33600 $\mathrm{kJ \cdot 24\ h^{-1}}$) an energy intake ranging between 3000 and 4000 $\mathrm{kcal \cdot 24\ h^{-1}}$ (12600–16800 $\mathrm{kJ \cdot 24\ h^{-1}}$) was sufficient to maintain adequate physical performance.

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