Original Paper DOI: 10.5604/20831862.1111849 Biol. Sport 2014;31:217-222

PHYSIOLOGICAL DEMANDS OF YOUNG WOMEN'S COMPETITIVE GYMNASTIC ROUTINES

Accepted for publication 23.01.2014

AUTHORS: Marina M., Rodríguez FA.

INEFC Barcelona, Av de l'Estadi sn. 08038, Barcelona, Spain

Reprint request to:
Michel Marina
INEFC Barcelona.
Av de l'Estadi sn. 08038. Barcelona. Spain
E-mail: michel.marina.1964@gmail.com

ABSTRACT: The objective of this study was to investigate the physiological indices of competitive routines in women's artistic gymnastics by characterizing post-exercise heart rate (HR), oxygen uptake (VO_2) and peak blood lactate concentration (L_{max}) in a group of eight young elite-oriented female gymnasts. HR was continuously monitored with Polar RS400 monitors during the test event simulating a competition environment. Within 5 s of the end of each routine, the breath-by-breath gas analyser mask was placed on the face to record VO_2. VO_2max was calculated by the backward extrapolation method of the VO_2 recovery curve. L_{max} was obtained during recovery (min 1, 3, 5, 7 and 10) subsequent to each event. One week later, HR, VO_2 and L_{max} were measured during an incremental continuous treadmill test. The treadmill test was confirmed as the assessment with the highest physiological demand. The gymnasts reached their highest values of HR (183-199 beats·min^{-1}), VO_2/Bm (33-44 ml·kg^{-1}·min^{-1}) and L_{max} (7-9 mmol·l^{-1}) in the floor and uneven bars exercises. The vault was the event with the lowest HR (154-166 beats·min^{-1}) and L_{max} (2.4-2.6 mmol·l^{-1}), and the balance beam had the lowest VO_2 (27-35 ml·kg^{-1}·min^{-1}). The mean relative peak intensities attained in the different events, which ranged from 65 to 85% of the individual VO_2max and HRmax recorded in the laboratory, suggest that cardiorespiratory and metabolic demands are higher than previously indicated. The high percentage of VO_2 measured, particularly after the floor event, suggests that aerobic power training should not be neglected in women's artistic gymnastics.

KEY WORDS: VO_2max, blood lactate, heart rate, artistic gymnastics

INTRODUCTION

Many authors have monitored and assessed physiological parameters in paediatric sport competitive populations [16]. Whereas heart rate (HR), oxygen uptake (VO_2) and blood lactate have been assessed in prepubescent athletes using treadmill [1,17,25], or bicycle ergometer tests [4], strength, power, flexibility and agility have traditionally been considered the most important attributes for success in artistic gymnastics [2,14]. Because artistic gymnastics require a combination of explosive and quasi-maximal contractions to perform many difficulties, HR has been reported to be generally high. Peak HR values around 170-190 beats·min^{-1} are usually recorded after the routines of senior male gymnasts [8,11], and around 150-180 beats·min^{-1} in females gymnasts [21]. Because similar peak HR values (160-190 beats·min^{-1}) were recorded in young boys and girls gymnasts [18], similar results are expected in our study.

Peak blood lactate concentrations (L_{max}) of 8-11 mmol·l^{-1} [8] and 3-6 mmol·l^{-1} [11] in adult male gymnasts, and around 4 mmol·l^{-1} in rhythmic gymnastics [9], support the idea of predominance of anaerobic glycolysis observed during gymnastic competitive routines 8,9,11,18,19], and it seems a good tool for physiological data collection in gymnasts [10]. Nevertheless, L_{max} of 20-28 mg% (equivalent of ~ 2.2-3.1 mmol·l^{-1}), reported in female prepubertal gymnasts [18], do not warrant the previous observation with prepubertal girls. Some authors [5] have reported lower glycolytic energy production in children due to lower phosphofructokinase activity. Children have lower blood lactate concentrations than adults at the same relative intensity [16] but similar VO_2max relative to body mass (VO_2max/Bm) than adults [29]. Physical training seems to increase the activities of anaerobic enzymes and substrates in children [5], though not in all cases [17]. Aside from the anaerobic nature of artistic gymnastics in senior gymnasts [11,14,26], it may be of interest to verify whether intensive gymnastics training could induce relatively high blood lactate concentrations in prepubescent female gymnasts while performing their competitive routines.

To estimate the degree of participation of the aerobic and anaerobic energetic pathways during competitive sport routines, HR and blood lactate assessment alone are not enough; oxygen uptake must also be analysed. In recent decades studies have assessed HR, VO_2 and blood lactate in laboratory or field situations in different forms of gymnastics. Initially, some of them used only HR [6,15], confining VO_2 assessment to laboratory situations in women's artistic gymnastics (WAG) [18,26,29], men's artistic gymnastics (MAG) [8, 13] and rhythmic gymnastics [1]. Interestingly, multifactorial studies assessing VO_2, HR and blood lactate have measured VO_2 only in laboratory conditions, using treadmill or cycloergometer tests [8,13,18]. Combined measurements of these three parameters, carried out during or just after the completion of competitive gymnastics routines, as we are going to do in this study, have been reported in rhythmic gymnastics [9], but not in artistic gymnastics (WAG & MAG). Functional ventilatory assessments that calculate the oxygen utilization from ventilated air in the course of maximal performance are more satisfactory, among other reasons because they depend much less on the athlete's body mass, which is far lower in gymnastics than in other sports [29]. However, in order to measure ventilatory parameters from the beginning to the end of gymnastic competitive routines, the use of portable telemetric analysers such as Kn-Cosmed would be required; because of participant discomfort and the instrumental risk induced by the acrobatic nature of MAG and WAG exercises, assessment of this kind has not been possible. So, another strategy would be to assess the ventilatory function just after the completion of the competitive routine. Post-exercise gas analysis using the Douglas bag technique [20] and the breath-by-breath system [23] have been successfully implemented to investigate oxygen consumption in swimming.

The objective of this study was to investigate the physiological indices of competitive routines in women's artistic gymnastics by characterizing the heart rate (HR), oxygen uptake (VO_2) and peak blood lactate concentration (L_{max}) after exercise in a group of young, well-trained female gymnasts competing at national and international level.

MATERIALS AND METHODS

Subjects. A group of eight young female artistic gymnasts participated in the study. Mean age was 13.5 ± 1.27 years, mean body mass 36.4 ± 4.64 kg, and mean height 145.2 ± 5.29 cm. Only three (aged over 14) had menarche, but did not have regular menstruation (less than four times a year). This group was elite-oriented, training up to 30 h per week over 12 weekly sessions. The study was approved by the Catalan Sports Administration's Clinical Research Ethics Committee. Parental permission and informed consent were obtained from all participants.

Instruments

The heart rate (HR) was continuously monitored with Polar RS400 HR monitors, with a setting of a 5 s interval between HR measurements (12 HR values per minute). Venous blood lactate was analysed using the photoenzymatic method (Boehringer Mannheim, RFA) and the methodology presented by Rodríguez et al. [24]. A treadmill (Woodway USA, Inc) was used for the laboratory test and tilted upwards 2.5% throughout the duration of the test. The breath-by-breath CPXII gas analyser (Medical Graphics, USA) was used to collect the oxygen uptake.

Field Test Procedure

The gymnasts performed the high-difficulty rating routines adopted for the specific competitive period during a simulated four-event competition, in the following order: vault, uneven bars, balance beam, and floor. A heart rate (HR) below 100 $beats \cdot min^{-1}$ was used as the criterion for sufficient recovery [18]. HR was continuously monitored and HR Polar Analysis Software was chosen to select the appropriate HR window data attributed to each of the four competitive events. In order to synchronize HR monitoring with the events performed by each gymnast, all Polar monitors and a video camera were manually activated at the same time with an acoustic signal. The video camera was positioned in order to obtain a general view of the gymnasium, to monitor the duration of the competitive gymnastic routines, and to control the movements or potential incidents of all the gymnasts in the study.

Capillary blood samples were collected at baseline and during the recovery (min 1, 3, 5, 7 and 10) subsequent to each event. To obtain direct data related to oxygen uptake and other related ventilatory parameters during gymnastic routines, a methodological strategy had to be selected. In spite of its availability, the Cosmed K4b2 Portable Metabolic System was not used during the gymnasts' acrobatic routines, because the nature of the exercise performed in artistic gymnastics would entail a significant risk for the equipment and above all an excessive degree of discomfort for the participant performing the routine. In order to be as ecological as possible during our metabolic assessment, the mask of the gas analyser was placed on the gymnast's face within 5 s of the end of each routine. The CPX analyser was placed within 3 m of the routine's dismount or exit. This methodological approach impedes the recording of the ventilatory parameters before and during the completion of the routine, but allows the assessment of the highest possible measures just after completion. This procedure was used successfully by Montpetit et al. [20]; called "backward extrapolation (BE) of the VO_2 recovery curve to time zero", it has proved to be a reliable, valid way to measure VO_2 peak after completion of maximal swimming. Time zero was considered as the moment when the gymnast had just finished her competitive routine.

Laboratory Test Procedure

One week after the test event simulating a competition environment, the participants performed a short continuous incremental treadmill test. After the first minute in the standing position on the treadmill, warm-up consisted in walking at a speed of 6 $km \cdot h^{-1}$ for 5 min. Thereafter, the speed increased progressively each minute until VO_2max could no longer increase. The same breath-by-breath analyser was used to record oxygen uptake. Heart rate was measured with the same HR Polar monitors.

Data Analysis

The parameters used in this study were: age (years), body mass (Bm; kg), height (cm), heart rate (HR; beats·min^{-1}), absolute (VO_2max; l·min^{-1}) and relative (VO_2max/Bm; ml·min^{-1}·kg^{-1}) maximal oxygen uptake, average peak blood lactate concentration (L_{max}; mmol·l^{-1}), and duration of the competitive gymnastic routines (s).

Statistics

Descriptive statistics were used to characterize the metabolic demand of the four competitive gymnastic routines and the treadmill test. Values were means and standard deviation (SD), confidence interval (CI), and maximal value of the group. The normal distribution of the variables was checked with the Shapiro-Wilk test, before using parametric statistical tests. The differences between the four competitive events and the treadmill test were studied with one-way repeated measure ANOVAs. Having in mind the small sample size of our study, the partial eta-squared (η^2) value was used to report effect sizes, statistical power was calculated for each variable, and post-hoc analyses with Sidak adjustment for multiple comparisons were implemented when appropriate. The level of significance was set at 0.05.

RESULTS

The values of heart rate, oxygen uptake, and blood lactate concentration measured during the competitive gymnastic routines (vault, uneven bars, balance beam, and floor) as well as their durations, and the treadmill test in the laboratory, are summarized in Table 1. The maximal blood concentrations were recorded at minute three or five of recovery in all gymnasts.

The treadmill test was confirmed as the assessment in which the gymnasts reached their highest values of HR and VO_2 ($p \leq 0.011$; Table 2). Among the competitive events, the highest values of HR, VO_2 and L_{max} were systematically recorded at the floor ($p \leq 0.045$; Table 2), followed in second place by the uneven bars (Table 1). The vault was the event with the lowest values of HR and L_{max} ($p \leq 0.001$),

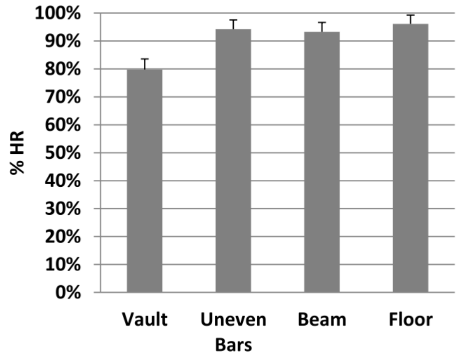

FIG. 1. PERCENTAGE OF THE HEART RATE (HR) MEASURED JUST AFTER THE ROUTINES ON THE APPARATUS WITH RESPECT TO THE HRMAX ASSESSED DURING THE TREADMILL TEST IN THE LABORATORY

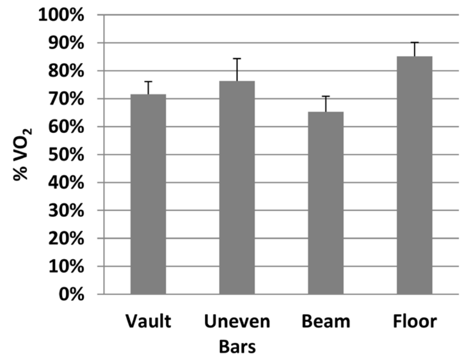

FIG. 2. PERCENTAGE OF THE VO_2 MEASURED JUST AFTER THE ROUTINES ON THE APPARATUS WITH RESPECT TO THE VO_2MAX ASSESSED DURING THE TREADMILL TEST IN THE LABORATORY

TABLE 1. PEAK VALUES OF THE METABOLIC PARAMETERS RECORDED DURING THE TREADMILL TEST AND THE FOUR COMPETITIVE ROUTINES ON THE APPARATUS.

		Routine Duration (s)	HRmax (beats·min^{-1})	VO_2max (L·min^{-1})	VO_2max/Bm (ml·min^{-1}·kg^{-1})	L_{max} (mmo·L^{-1})
	M ± SD		201.1 ± 6.6	1.74 ± 0.26	47.90 ± 4.03	
Treadmill Test	CI	--	(187 – 196)	(1.56 – 1.93)	(45.15-50.72)	--
	max		210	2.15	56.40	
	M ± SD		164.4 ± 8.1	1.22 ± 0.20	34.27 ± 7.64	2.5 ± 0.2
Vaulting	CI	5.14 ± 0.23	(154 – 166)	(1.08 – 1.36)	(28.96-39.64)	(2.4 – 2.6)
	max		174	1.41	40.29	4.7
	M ± SD		189.1 ± 8.7	1.31 ± 0.06	36.59 ± 4.62	7.4 ± 0.8
Uneven bars	CI	27.88 ± 5.30	(183 – 196)	(1.27 – 1.35)	(33.41-39.79)	(6.9 – 7.9)
	max		200	1.48	42.02	8.6
	M ± SD		184.6 ± 7.1	1.14 ± 0.25	31.28 ± 6.06	4.3 ± 1.1
Balance beam	CI	85.75 ± 1.67	(180 – 190)	(0.97 – 1.31)	(27.07-35.53)	(3.5 – 5.1)
	max		202	1.35	38.57	8.8
	M ± SD		195.3 ± 6.3	1.48 ± 0.19	40.73 ± 4.19	7.9 ± 1.8
Floor	CI	86.50 ± 1.60	(191 – 199)	(1.35 – 1.61)	(38.03-43.57)	(6.7 – 9.2)
	max		203	1.72	50.29	10.5

Note: M = mean; SD = standard deviation; CI = confidence interval (95%); max = maximal value

TABLE 2. COMPARISONS BETWEEN THE VALUES REGISTERED IN THE TREADMILL TEST AND THE FOUR COMPETITIVE EVENTS USING THE ONE-WAY REPEATED MEASURE ANOVAS.

Variable	F	df	p	η2	Power	Post-hoc	p
HR_{max} (beats·min^{-1})	61.52	4, 7	< 0.001	0.90	1	0 > 1, 2, 3, 4	< 0.011
						1 < 2, 3, 4	< 0.001
VO_2max (L·min^{-1})	55.98	4, 7	< 0.001	0.89	1	0 > 1, 2, 3, 4	< 0.001
						0 > 4 > 2 > 1 > 3	≤ 0.045
VO_2max/Bm (mL·min^{-1}·kg^{-1})	77.40	4, 7	< 0.001	0.92	1	0 > 1, 2, 3, 4	< 0.001
						4 > 2 > 1 > 3	≤ 0.040
L_{max} (mmol·L^{-1})	27.66	4, 7	< 0.001	0.80	1	1 < 2, 3, 4	< 0.001
						4 > 2 > 3	≤ 0.018
Normalized data (%) respect to treadmill test							
% HR_{max}	51.94	3, 7	< 0.001	0.88	1	1 < 2, 3, 4	< 0.001
% VO_2max/Bm	30.64	3, 7	< 0.001	0.81	1	1, 2, 3 < 4	≤ 0.004
						2 > 3	≤ 0.012

Note: The parameters used for comparison are: maximal heart rate (HR_{max}), absolute (VO_2max) and relative (VO_2max/Bm) oxygen uptake, and blood lactate (L_{max}). Strength of the difference (F value), degree of freedom (df), partial eta square (η2) used to report the effect size, statistical power (Power), level of significance (p) of the F value and post-hoc analysis. Events numbering: Treadmill test = 0; vault=1, uneven bars = 2; balance beam = 3; floor = 4.

and the lowest VO_2 values were recorded at the balance beam (p≤0.045; Table 2). Finally the HR values for the balance beam were very high, very close to the ones recorded for the floor and uneven bars exercises (Table 1).

In addition to these raw metabolic data, the relative values (in percentages) with respect to the treadmill test scores in the laboratory are of great interest (Figures 1 and 2). The three exercises other than the vault induced very high relative HR values, above 90% (Figure 1). As far as oxygen uptake is concerned, the floor was the most demanding event (85.1%) and the balance beam the least demanding (65.3%) (Figure 2).

DISCUSSION

Heart Rate. In spite of the linear relation between VO_2 and HR below maximal and supramaximal intensities, the use of HR as an indicator of the intensity of physical activity may appear to be an oversimplification [6]. Emotional involvement [18] or prolongation of isometric muscular contraction [28] during gymnastics routines may increase the HR without a concomitant VO_2 increase. Even considering the HR overshoot typically observed after gymnastics routines [8], energy expenditure requirements cannot be extrapolated from the relationship between VO_2 and HR assessed during laboratory tests, as some authors have done [19], because conceptually gymnastics is very different from running [13]. The very short vault routines, whose L_{max} values confirmed the alactic anaerobic nature of these exercises, can be considered an exception. In comparison to the much longer beam and floor routines, we advise against using maximal values of HR and VO_2 to report exercise intensity in vault. Certainly a biomechanical approach instead of a physiological one could bring more appropriate assessments such as the mechanical power developed during the jump or during the rebound against the vault platform, to report exercise intensity.

Nevertheless, accurate HR recording before, during and after sport activity is easily obtained and can be considered a useful first approach to assess exercise intensity in technical-combinatory sports such as gymnastics [6,18]. HRmax around 200 beats·min^{-1} seems to be easily reached with laboratory tests in paediatric populations without the need for any elite sport orientation [1,17]. This figure is in line with HR values reported in female artistic gymnasts [18], rhythmic gymnasts [1,9], and young female dancers [1].

Five decades ago, Kozar [15] registered HR values between 150 and 170 beats·min^{-1} after the completion of gymnastics events in a single case study (male artistic gymnast). The higher level of difficulty and the longer duration of today's competitive routines [12-14] can account for the fact that HR values were above 180 beats·min^{-1} in all events but the vault, and confirm the results of previous studies in female gymnasts of similar age [18]. The lower HR values reported in adult male [8,11] and female [21,27] gymnasts after their competitive routines may be attributed to age [18].

Our relative HRmax values (93% of laboratory values) confirm the maximal demand of the cardiac pump during artistic [18] and rhythmic [9] gymnastic competitive routines. Whereas in our study the floor was the most physiologically demanding WAG event, other studies [18] have found the uneven bars to be the most challenging; in both that study and our own, HR and lactate values reached in the beam exercise were very high. Possibly, the danger factor, anxiety and the increase in isometric contraction associated with balance beam performance are responsible for this behaviour [18].

The observation that the greater difficulty of the competitive routine induced higher HR values within a few seconds (increases of 15-20 beats·min^{-1} with respect to the previous "more basic" routine) 15] may partially explain why the three best performing gymnasts in our group obtained the highest values of HR, VO_2 and blood lactate after their competitive routines. This finding is corroborated by Montgomery & Beaudin's [18] observation of lower HR and lactate values in low-ability than in high-ability gymnasts after their competitive routines.

The higher cardiorespiratory and metabolic demands observed in our gymnasts may be attributed to the greater difficulty of the routines that characterize WAG today.

Blood Lactate

It has been estimated that male gymnasts use only 20% of their maximal aerobic power and that the contribution from anaerobic sources is as high as 80% [19]. This suggestion has been corroborated by other authors [8,11], who also confirmed the significant role of anaerobic glycolysis in MAG by assessing L_{max} after the completion of their competitive routines. For their part, female gymnasts aged 11 to 13 reached a mean L_{max} of 48 to 52% of the laboratory value following their competitive routines [18].

The L_{max} values obtained in the floor and uneven bars by our female gymnasts are very similar to the ones recorded in incremental treadmill tests in normal active children [22], rhythmic gymnasts and young female dancers [1] and athletic populations of similar age [17]. Probably because of their sex and age [16] our gymnasts' L_{max} values are lower than those reported in adult male elite gymnasts [8], who evidently have greater muscle mass. Surprisingly, however, our L_{max} values recorded in the floor and uneven bars were higher than those reported by Jemni et al. (2000) in five MAG exercises. In both MAG and WAG, the vault is the event with the lowest L_{max} [11,14,18]. Bearing in mind that the anaerobic threshold is set at L_{max} values ranging from 2 to 3 $mmol \cdot l^{-1}$ in prepubescent male athletic groups [17], and around 4 $mmol \cdot l^{-1}$ in rhythmic gymnasts and young female dancers [1], the anaerobic pathway appears to play a major role in our female gymnasts in the uneven bars and floor events. In fact, the best gymnasts in our group reached L_{max} values close to 9-10 $mmol \cdot l^{-1}$ after the completion of their competitive routines.

The acidosis associated with lactate accumulation has several effects on the contractile process in muscle [7]. It may therefore impair a performance based on grace, postural control and coordination choreographed to music [1]. This may also be the case in the balance beam and floor exercises.

Oxygen Uptake

Endurance sports such as running, cycling, cross-country skiing and swimming have traditionally been considered to be much more dependent on aerobic power than more intense, explosive and short duration sports such as athletic jumps, gymnastics, weightlifting and diving, which are thought to rely more on anaerobic power. Thus, as expected, our VO_2max values were lower than those reported for female adolescent elite endurance athletes [3] and swimmers [30]. Although the small body size of the gymnasts (particularly in the case of females) is reflected in absolute VO_2max values clearly lower than those recorded in other aerobic sports, when body mass is taken into account in the assessment of VO_2max/Bm the differences may decrease substantially [29] although not to the point of reaching equivalence. Compared with other anaerobic sports, the VO_2max/Bm obtained on the treadmill test by our gymnasts was very similar to the values obtained by control groups of similar age [17,22,25], higher than rhythmic gymnasts in some studies [29] but lower in others [9], and lower than other athletes such as sprint runners and weight lifters [17], swimmers [4], and wrestlers [25].

In comparison to other studies of female gymnasts [1,18,21], our range of VO_2max/Bm values is higher than in adolescent WAG [29], lower than in adult WAG [21], and similar to other prepubertal WAG data [18]. As regards physiological data in MAG and WAG, Jemni et al. (2001)'s overall review of the literature confirmed that little has changed with respect to oxygen uptake and HRmax over the last four decades.

Finally, we stress the high relative VO_2 values (from 65 to 85% of treadmill VO_2) obtained in the competitive routines, and particularly in the floor exercise. These relative VO_2 values indicate very fast oxygen kinetics in these high-level gymnasts, and classify them as "high-ability gymnasts" according to Montgomery and Beaudin's [18] criteria. The possibility of reaching 85% of VO_2max in floor routines suggests that aerobic training in WAG should not be underestimated.

Practical Application

Two main types of training (strength training and aerobics) are used in the preparation of athletes depending on the type of sport. There is no doubt that strength, flexibility and mechanical and anaerobic power are the primary factors in MAG and WAG performance [14]. Nevertheless, in spite of the criticisms made by some authors of the need to develop VO_2max in MAG [13], the high percentage of VO_2 measured immediately after WAG competitive routines compared with the treadmill test (especially in the floor exercise) suggests that aerobic power training should not be neglected in female artistic gymnasts. Possibly the inclusion of music and the greater importance of choreographic elements in the floor event mean that these routines are more continuous than the ones that MAG gymnasts perform. Therefore, it may be that female gymnasts benefit much more from aerobic power training than males, who have more strength, power and muscle mass. The lower but still high percentages of VO_2 compared with the treadmill test measured in the other three events do not contradict this recommendation.

CONCLUSIONS

Exercise duration and intensity showed considerable variability between subjects and between the four gymnastic competitive events. In spite of their short duration, mean peak intensities from 65 to 85% of the individual oxygen uptake were attained in the different exercises. L_{max} values were lower in the vaulting and balance beam than in the uneven bars and floor events. It appears that modern female competitive gymnastics imposes higher cardiorespiratory and metabolic demands than was previously supposed.

Acknowledgments

We are grateful to the WAG coach Eric Boucharin for his contribution to the study.

REFERENCES

1. Baldari C., Guidetti L. VO2max, ventilatory and anaerobic thresholds in rhythmic gymnasts and young female dancers. J. Sports Med. Phys. Fitness 2001;41:177-182.
2. Bale P., Goodway J. Performance variables associated with the competitive gymnast. Sports Med. 1990;10:139-145.
3. Burke E., Brush F. Physiological and anthropometric assessment of successful teenage female distance runners. Res. Q. Exerc. Sport 1979;50:180-187.
4. Cunningham D.A., Eynon R.B. The working capacity of young competitive swimmers, 10-16 years of age. Med. Sci. Sports 1973;5:227-231.
5. Eriksson B.O., Gollnick P.D., Saltin B. Muscle metabolism and enzyme activities after training in boys 11-13 years old. Acta Physiol. Scand. 1973;87:485-497.
6. Faria I.E., Phillips A. A study of telemetred cardiac response of young boys and girls during gymnastics participation. J. Sports Med. 1970;10:145-150.
7. Gollnick P.D., Bayly W.M., Hodgson D.R. Exercise intensity, training, diet, and lactate concentration in muscle and blood. Med. Sci. Sports Exerc. 1986; 18: 334-340
8. Goswami A., Gupta S. Cardiovascular stress and lactate formation during gymnastic routines. J. Sports Med. Phys. Fitness 1998;38:317-322.
9. Guidetti L., Baldari C., Capranica L., Persichini C., Figura F. Energy cost and energy sources of ball routine in rhythmic gymnasts. Int. J. Sports Med. 2000; 21:205-209.
10. Heller J., Tuma Z., Dlouha R., Bunc V., Novakova H. Anaerobic capacity in elite male and female gymnasts. Kinanthropologica 1998;34:75-81.
11. Jemni M., Friemel F., Lechevalier J.M., Origas M. Heart rate and blood lactate concentration analysis during a high-level men's gymnastics competition. J. Strength Cond. Res. 2000;14:389-394.
12. Jemni M., Friemel F., Sands W.A., Mikesky A. Evolution of the physiological profile of gymnasts over the past 40 years. A review of the literature. Can. J. Appl. Physiol. 2001;26:442-456.
13. Jemni M., Sands W.A., Friemel F., Stone M.H., Cooke C.B. Any effect of gymnastics training on upper-body and lower-body aerobic and power components in national and international male gymnasts? J. Strength Cond. Res. 2006; 20: 899-907
14. Jemni M., Sands W.A., Salmela J.H., Holvoet P., Gateva M. The Science of Gymnastics. 1 ed. London: Routledge, Taylor & Francis Group; 2011
15. Kozar A.J. Telemetred heart rates recorded during gymnastics routines. The Research Quarterly 1963;34:102-107.
16. Malina R.M., Bouchard C., Bar-Or O. Growth, Maturation and Physical Activity. Champaign Illinois: Human Kinetics; 2004.
17. Mero A., Kauhanen H., Peltola E., Vuorimaa T., Komi P.V. Physiological performance capacity in different prepubescent athletic groups. J. Sports Med. Phys. Fitness 1990;30:57-66.
18. Montgomery D.L., Beaudin P.A. Blood lactate and heart rate response of young females during gymnastic routines. J. Sports Med. Phys. Fitness 1982;22:358-365.
19. Montpetit R.R. Physiology of gymnastics. In: Salmela J.H. ed, The advanced study of gymnastics. Springfield: CC Thomas;1976:183-217.
20. Montpetit R.R., Leger L.A., Lavoie J.M., Cazorla G. VO2 peak during free swimming using the backward extrapolation of the O2 recovery curve. Eur. J. Appl. Physiol. Occup. Physiol. 1981;47:385-391.
21. Noble L. Heart rate and predicted VO2 during women's competitive gymnastic routines. J. Sports Med. Phys. Fitness 1975;15:151-157.
22. Paterson D.H., Cunningham D.A., Bumstead L.A. Recovery O2 and blood lactic acid: longitudinal analysis in boys aged 11 to 15 years. Eur. J. Appl. Physiol. Occup. Physiol. 1986;55:93-99.
23. Rodríguez F.A. Oxygen cost of front crawl swimming measured by „breath by breath" gas analysis during recovery in swimmers and water polo players. 1st Annual Congress of the ECSS; 1996:486-487. Nice, France
24. Rodriguez F.A., Banquells M., Pons V., Drobnic F., Galilea P.A. A comparative study of blood lactate analytic methods. Int. J. Sports Med. 1992;13:462-466.
25. Sady S.P., Thomson W.H., Berg K., Savage M. Physiological characteristics of high-ability prepubescent wrestlers. Med. Sci. Sports Exerc. 1984;16:72-76.
26. Sands W.A., Caine D.J., Borms J. Scientific aspects of women's gymnastics. Baser, Switzerland: Karger; 2002
27. Seliger V., Budka I., Buchberger J., Dosoudil F., Krupova J., Libra M., Yabe K. Métabolisme énergétique au cours des exercise de gymnastique. Kinanthropologie 1970;2:159-169.
28. Sharkey B.J., McDonald J.F., Corbridge L.G. Pulse rate and pulmonary ventilation as predictors of human energy cost. Ergonomics 1966;9:223-227.
29. Sprynarova S., Parizkova J. Comparison of the functional, circulatory and respiratory capacity in girl gymnasts and swimmers. J. Sport Med. and Phys. Fitness 1969;9:165-171.
30. Unnithan V., Holohan J., Fernhall B., Wylegala J., Rowland T., Pendergast D.R. Aerobic cost in elite female adolescent swimmers. Int. J. Sports Med. 2009;30:194-199.