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ESTIMATION OF SUBMAXIMAL EXERCISE STROKE VOLUME OF MEXICAN ATHLETES SUPPORTS PERIPHERAL ADJUSTMENT IN VO_2 MAX

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ABSTRACT

Padilla JP, Castillo-Hernández MC, Castillo-Henkel C. Peripheral Rather than Central Factors Control the VO_2 with Exercise. **JEPonline** 2011;14(3):80-90. The purpose of this study was to determine if the assumed difference in the athletes' (ATH) submaximal (Subm) exercise stroke volume (SV, $mL\cdot beat^{-1}$) was due to an endurance adaptation of different proportion in relation to Subm heart rate (HR); absolute (VO_2 max, $L\cdot min^{-1}$) and relative oxygen uptake (VO_2 max, $mL\cdot min^{-1}\cdot kg^{-1}$). Subjects were (N=57) 26 ± 9 yrs old, 171±6 cm of stature, and TBM of 66±9 kg. The sample was divided into non-athletes (n=11) and ATH of diverse sport specialties (n=41) who were ranked either at national or international level. The ATH were then regrouped in 5 groups: 30, (n=8 =39 $mL\cdot min^{-1}\cdot kg^{-1}$), 40, (n=11, =49 $mL\cdot min^{-1}\cdot kg^{-1}$) 50, (n=8, =59 $mL\cdot min^{-1}\cdot kg^{-1}$), 60, (n=7, =69 $mL\cdot min^{-1}\cdot kg^{-1}$), and 70, (n=4, =79 $mL\cdot min^{-1}\cdot kg^{-1}$) ($VO_2$ maxRelATH). We applied a maximum effort test using a cycle ergometer with direct measurement of VO_2 at 2240 m of altitude. The average of the SV was obtained from the relation between VO_2 and HR with a slope $?VO_2/?HR$ and a stable value of 1 / $[O_2]$ arterial = ½ •10. The ergometric power max, the index of ergometric power max, VO_2 max, and SV were significantly greater in the ATH (138 mL) versus the non-athlete (86 mL). But, SV was not significantly different between the groups classified by VO_2 maxRel (VO_2 maxRelATH). The similar SV between VO_2 maxRelATH groups is explained by a probable dissociation between the central and peripheral components during the endurance adaptation (i.e., the practice of each sport specialty imposes on the athlete's VO_2 maxRelATH). The findings support the contention that SV distinguishes the differences in this variable between the ATH and non-athletes but not between the VO_2 maxRelATH groups.

Key Words: Endurance, Sport Specialties, Oxygen Uptake, Heart Rate

INTRODUCTION

There is significant individual variability in the cardiac adaptations that occur in response to exercise training. Factors associated with this variability are continuously being investigated (3, 27). In particular, there is the question of whether a difference in systolic volume exists as a function of different degrees of training among athletes (30). The determinant of the cardiovascular response to exercise is likely to be related to the type of training athletes engage in. In general, exercise training is either dynamic (isotonic) or static (isometric), although most types of exercise are a combination of the two (13). In the static exercise, there is an increase in muscle tension that changes little its length. Dynamic exercise (e.g., running and swimming) changes the length of the muscles and there is a minimum of tension. The physiological consequences of training are numerous, particularly the increase in health and well-being. Most notably, there is an increase in oxygen consumption (VO_2) that allows for an increase in energy for muscle contraction.

By rearrangement of the Fick equation ($VO_2 = Q \times a\text{-}\bar{v}O_2$ diff), it is clear that the increase in VO_2 with exercise is due to the central adjustment (Q) and/or the peripheral adjustment ($a\text{-}\bar{v}O_2$ diff) to the muscles' need for more oxygen. Endurance trained athletes adjust to the need for an increase in energy for muscle contraction by both an increase in Q (primarily by way of stroke volume, SV) and increased tissue extraction ($a\text{-}\bar{v}O_2$ diff). Different types of sportive events render the respective athletes more likely or less likely to increase VO_2 by way of SV. Athletes in sports of short duration and maximal intensity are more likely to respond with a high HR to increase Q (9). On the other hand, maximal VO_2 is substantially higher in endurance athletes. But, of course, there are different levels of VO_2 max as defined by the specifics of different endurance sports (6,18).

Oxygen pulse (O_2 pulse) is the quantity of O_2 that is absorbed during a cardiac cycle. It represents the average of VO_2 in the course of one cardiac period (systole plus diastole). The VO_2 per minute is divided by the HR to get the average O_2 consumption in the course of a heart beat of average duration. Oxygen pulse depends on the SV and arteriovenous oxygen difference ($a\text{-}\bar{v}O_2$ diff) (23). In terms of the Fick equation, if $a\text{-}\bar{v}O_2$ diff is held constant, then VO_2 changes as a function of cardiac output (Q). Since Q is the product of heart rate (HR) and SV, a decrease in HR reflects an increase in SV for a given Q. For that reason, the determination of the O_2 pulse during an ergometric effort provides valuable information about cardiac power (26). Consequently, if O_2 pulse is increased following participation in a specific sport, it is appropriate to conclude that SV is increased. In general, with the increase in SV, one can expect that both the absolute VO_2 max ($mL{\cdot}min^{-1}$) and the relative VO_2 maxRel ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$) are increased as well (2,14).

The evaluation of the resting cardiac function offers little information as to the cardiovascular reserve. This is the reason why an effort test allows researchers to evaluate the integrity of the left ventricle to contribute an adequate blood volume that satisfies the demands of oxygen at the cellular level. In short, the increase in energy metabolism during exercise allows for the determination of peripheral aerobic metabolic capacity (25). Athletes have greater cardiac reserve associated with a greater left ventricular size compared with those in non-athletes (21). Highly trained endurance athletes have a low resting heart rate with an increase in left ventricular size that accommodates an increase in end-diastolic volume (EDV). The size of the EDV sets the stage for an increase in the stretch of ventricles that result in a greater SV and, thus the potential for a superior Q and VO_2 max (21).

Several methods of study of the heart exist to evaluate the function of intermittent pump; among them exists, the cardiac catheterism, the cardiac scintillography during effort with ^{201}Ta, two-dimensional heart ultrasound, phono-cardiography, Doppler cardiography, electrocardiography, cardiac fluoroscopy and cardiac image contrast (3,8) in which the determination of the SV can serve as a useful indicator of the physiological relation between the size of the heart and the cardiac adaptations specific to different types of sports training (21). In particular, it is well known that aerobic training is associated with a larger resting SV and left ventricular ejection fraction (7).

Exercise SV can be estimated from asymptotic O_2 pulse (26). This is an important noninvasive technique that obviates vascular cannulation, thus allowing for the determination of SV during exercise. More often than not, athletes with high SV values also have a high VO_2 max as well as the propensity for a high level of physical activity (26). Hence, if the systolic volume of Mexican athletes of different sport specialties is caused by a sportive adjustment of different proportion in terms of maximum aerobic power (VO_2 max), then, it seems appropriate to conclude that significant differences in SV among these groups of athletes should be apparent.

METHODS

Volunteers

Fifty-seven subjects (46 athletes and 11 non-athletes) volunteers to participate in this study. All were clinically healthy with no contraindications to undergoing a maximum effort test (1). Each subject signed an inform consent prior to testing.

Procedures

Groups

The non-athletes (n=11) were from the Escuela Superior de Medicina, Instituto Politécnico Nacional. None participated in a program of sport preparation. The athletes (n=46) and their sport specialties were grouped in five areas (as defined by their VO_2 maxRel): Thirty (=39 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$) = rowing (n=2) + body building (n=4) + walk (n=1) + athletics (n=1); Forty (=49 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$) = karate-do (n=6) + rowing (n=3) + walk (n=1) + marathon (n=1); Fifty (=59 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$) = karate-do (n=3) + rowing (n=3) + walk (n=1) + marathon (n=1); Sixty (=69 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$) = marathon (n=2) + athletics (n=2) + karate-do (n=1) + walk (n=1) + body building (n=1) and; Seventy (=79 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$) = athletics (n=2) + marathon (n=1) + walk (n=1).

General Anthropometry

The total body mass and stature were measured using a clinical scale (Bame, model 420) calibrated previously to each measurement (24). Total body mass in kilograms was obtained after 12 hrs of fasting in each subject. Height in centimeters was measured on each subject while on the clinical scale.

Maximum Effort Test

Open-circuit spirometry was used to measure VO_2 max while the subject performed an incremental test on a electronic bicycle ergometer (17). Exercise ventilatory gas was collected and measured, during the last minute of each power output, with a Tissot gasometer, oxygen concentration by a electrochemical O_2 analyzer (Medical Analyzer IL404), and CO_2 concentration by an infrared CO_2 analyzer (Medical Analyzer IL200). The VO_2 max was defined as the highest VO_2 value attained at volitional fatigue (Power max), at a respiratory exchange ratio greater than 1, and at maximum heart rate (HR max, which coincided with or was higher with the subject's age-predicted value).

The bicycle ergometric test was conducted using a electronically braked cycle ergometer (Collins, Pedal Mate) with a continuous, multistage exercise procedure (17). The initial power output was set at 50 W, which was maintained for the first 2 min (17). Thereafter, the power output was increased by 25 W every minute until the subject could not sustain a pedalling rate of 60 rpm. Heart rate was electronically monitored at rest and every minute during the test. All testing took place in the laboratory between 7 a.m. and 10:30 a.m., and all athletes performed the test at the end their athletic season.

Maximum power index was derived by dividing Power max (i.e., the highest VO_2) by total body weight (in kg). Maximum HR was estimated by subtracting the subject's age from 220. The absolute VO_2 max value was divided by the total body weight to obtain the relative maximum VO_2 ($mL \cdot min^{-1} \cdot kg^{-1}$), which is an excellent indicator of the degree of adaptation of sport endurance (12), and in accordance with the O_2 pulse equation (as derived from the Fick equation):

$$VO_2 / HR = [(Q \bullet O_2 \text{ arterial content}) / HR] - [(Q \bullet O_2 \text{ mix venous content}) / HR]$$

Therefore, by rearranging the variables in the formula to systolic (stroke) volume (SV) can be estimated as submaximal exercise (SV) according to Whipp (26):

$$VO_2 / HR = (SV \bullet O_2 \text{ arterial content}) - [(Q \bullet O_2 \text{ mix venous content}) / HR]$$

Also, for all practical purposes, both the $Q \bullet O_2$ mix venous content and the O_2 arterial content are constant over a wide range of steady-state work rates (11,26), thus:

$$SV\ (mL \bullet beat^{-1}) = 5\ (lO_2 \text{ arterial} \bullet l\,blood^{-1}) \bullet ?VO_2\ (mL \bullet min^{-1}) / ?HR\ (mL \bullet min^{-1})$$

where "e" corresponds to the submaximal exercise of the relation between ∇O_2 and HR with a slope $?VO_2 / ?HR$ and 5 is stable value of $1 / [O_2]$ arterial = ½ • 10 (11).

Statistical Analyses

Anthropometric, resting data, and maximal exercise test data were analyzed using a one-way analysis of variance. When the results were significant at 0.05, the Tukey and Mann-Whitney *post hoc* test was used to locate differences between the groups. Pearson correlation coefficient analyses in the total sample and in the sport groups were used to evaluate the degree of relationships between the data. The Student´s t-test was used to determine if the mean values of two groups were significantly different (29).

RESULTS

The anthropometric, vital signs, and maximum ergoespirometric characteristics of the non-athletes and athletes are shown in Table 1, and those of the athletes regrouped based on their VO_2 maxRel are shown in Table 2. The SV of the non-athletes and athletes are shown in Figure 1 and those of the athletes regrouped based on their VO_2 maxRel are shown in Figure 2. In the total sample, the existing relationship between the SV and VO_2 maxRel was VO_2 maxRel = 32.163 + (0.148 • SV), r = 0.50, $P<0.001$; and the existing relationship between SV and resting HR was HR resting = 74.811 - (0.118 • SV), r = 0.50, $P<0.001$.

Table 1. Descriptive data of the subjects.

Variable	Non–Athletes	Athletes
General Anthropometry		
Sample size	11	46
Age (yrs**)**	27±10	26±9
Stature (cm)	169±5	171±6
Total Body Mass (kg)	68±7	66±10
Resting Data		
Heart Rate (beats•min^{-1})	66±8	59±12
DBP (mmHg)	68±19	67±9
SBP (mmHg)	109±20	111±14
Maximum Data		
Power (Watts)	186±23[a]	229±40[b]
Index of Power (W•kg^{-1})	7.9±1.3[c]	10.4±1.9[d]
Heart Rate (beats•min^{-1})	189±15	183±14
VO_2 (L•min^{-1})	2.7±0.6[e]	3.5±0.8[f]
VO_2 (mL•min^{-1}•kg^{-1})	40±10[g]	54±13[h]

Mean ± SD data; Pairs of different letters in superscript are significant differences determined by the Student's t-test. a ? b sum of ranks test of Mann-Whitney ranks, T = 160 (P < 0.002); c ? d, t = 4.12 (P < 0.05), e ? f, t = 2.9 (P < 0.007), g ? h, t = 3.254 (P < 0.05). VO_2 = Maximal aerobic power.

Analysis between Groups
Non-Athletes vs. Athletes
Maximum Ergometric Power

The Student t-test analysis of the non-parametric sum of ranks Mann-Whitney test, demonstrated that the maximum ergometric power was greater in athletes compared with non-athletes (Table 1).

Maximum Aerobic Power

The Student t-test demonstrated that both absolute VO_2 max and VO_2 maxRel were greater in athletes compared with non-athletes (Table 1).

Submaximal HR Response

The athletes compared with the non-athletes showed a significantly smaller HR response during the submaximal exercise (except during the first two min of the exercise) (Figure 3).

SV

The Student t-test demonstrated that the SV was greater (t=3.751, P<0.05) in the athletes compared to the non-athletes (Figure 1).

SV Analysis post hoc between VO_2 maxRel Groups

The ANOVA *post hoc* Tukey showed a significant difference (F=171.127, P<0.05) between all the sports groups based on their VO_2 maxRel (Thirty< Forty< Fifty< Sixty< Seventy) (Figure 2A), but there were no significant differences between these groups for SV (Figure 2B).

Table 2. Descriptive data of the athletes regrouped based on their maximum aerobic power relative to total body mass.

VO_2 (mL•min^{-1}•kg^{-1}) Variable	Thirty (=39)	Forty (=49)	Fifty (=59)	Sixty (=69)	Seventy (=79)
General Anthropometry					
Sample size	8	11	8	7	4
Age (yrs)	31±5	23±2	28±3	28±4	26±1
Stature (cm)	172±3	172±2	174±2	167±2	170±1
Total Body Mass (kg)	69±4	64±3	68±2	60±2	59±2
Resting Data					
Heart Rate (beats•min^{-1})	57±3	62±5	58±3	56±5	52±3
DBP (mmHg)	69±4	68±4	67±4	69±3	66±4
SBP (mmHg)	111±8	114±3	114±5	108±4	104±6
Maximum Data					
Power (Watts)	210±12	218±13	241±16	225±10	231±22
Index of Power (W•kg^{-1})	9±1	10±1	11±1	11±1	11±1
Heart Rate (beats•min^{-1})	180±4	186±6	185±4	180±6	178±1
VO_2 (L•min^{-1})	2.5±0.15[a,c]	2.9±0.13[a,c]	3.6±0.11[a]	3.9±0.14[d]	4.3±0.2[b]

Mean ± SD data. Pairs of different letters in superscript are significant differences determined by the one-way ANOVA and the *post hoc* Tukey test. a ? b, c ? d (F_{index} = 21.999, P <0.05). VO_2, maximal aerobic power.

DISCUSSION

Analysis between Groups

Maximum Ergometric Power

Both the maximum ergometric power and the index of maximum ergometric power were greater in athletes compared to the non-athletes. This finding is expected since it is common knowledge that exercise training increases aerobic power (12), enhanced neuromuscular responses, and skeletal muscle adaptations to sports training (22).

Maximum Aerobic Power

It was expected that the absolute and relative VO_2 max responses would be greater in the athletes versus the non-athletes. This finding is a function of the training in the different types of endurance training (4). Athletes have a higher maximum Q and VO_2 max (21) than non-athletes.

Submaximum Exercise HR

Athletes compared with the non-athletes showed a significantly lower submaximal exercise HR (11), which is a positive reciprocal response to the increase in submaximal exercise SV at the same absolute work load (7,28).

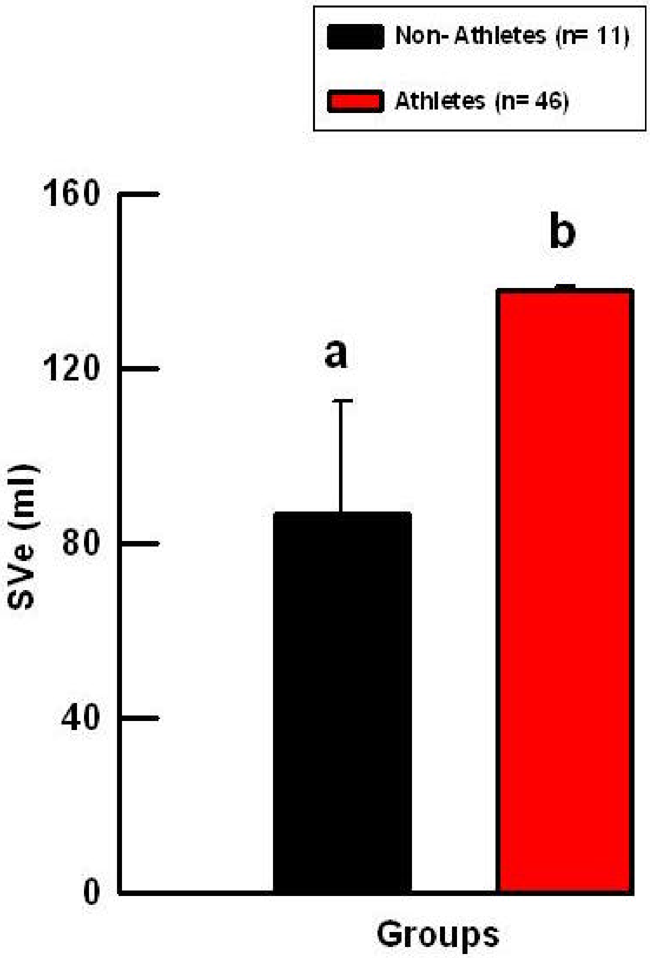

Figure 1. Mean submaximal stroke volume (SV) responses for athletes (red) and non-athlete (black). P<0.05; Student's t-test.

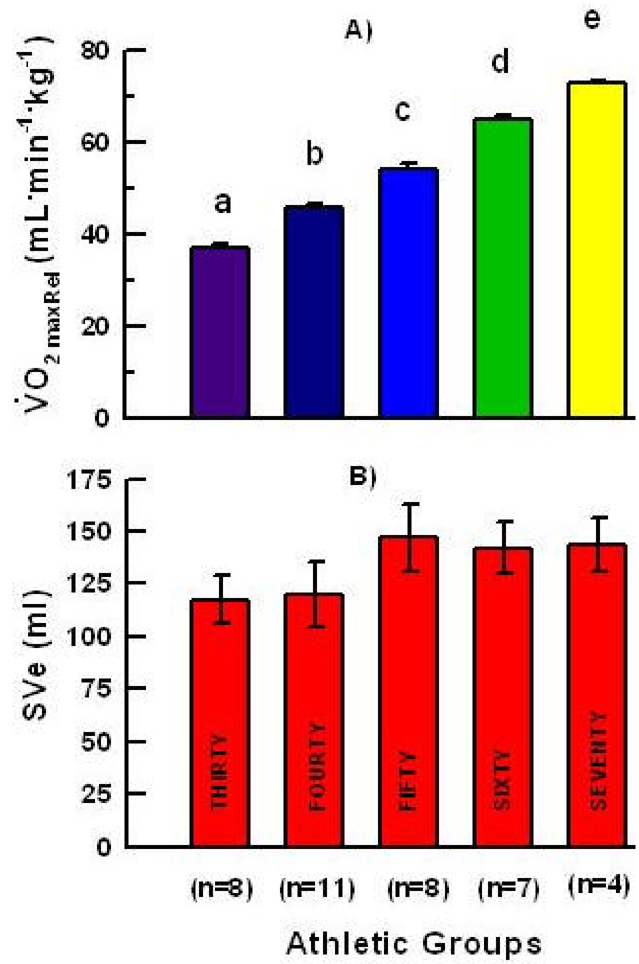

Figure 2. Maximal VO_2 relative to total body mass and submaximal SV of sports based on VO_2 max. The size of the bar and its vertical line are the mean ± SEM. The number between parenthesis is the sample size of each group. Each pair of different letters is a significant difference ($P<0.05$) between groups, as determined by means of ANOVA-*post hoc* Tukey.

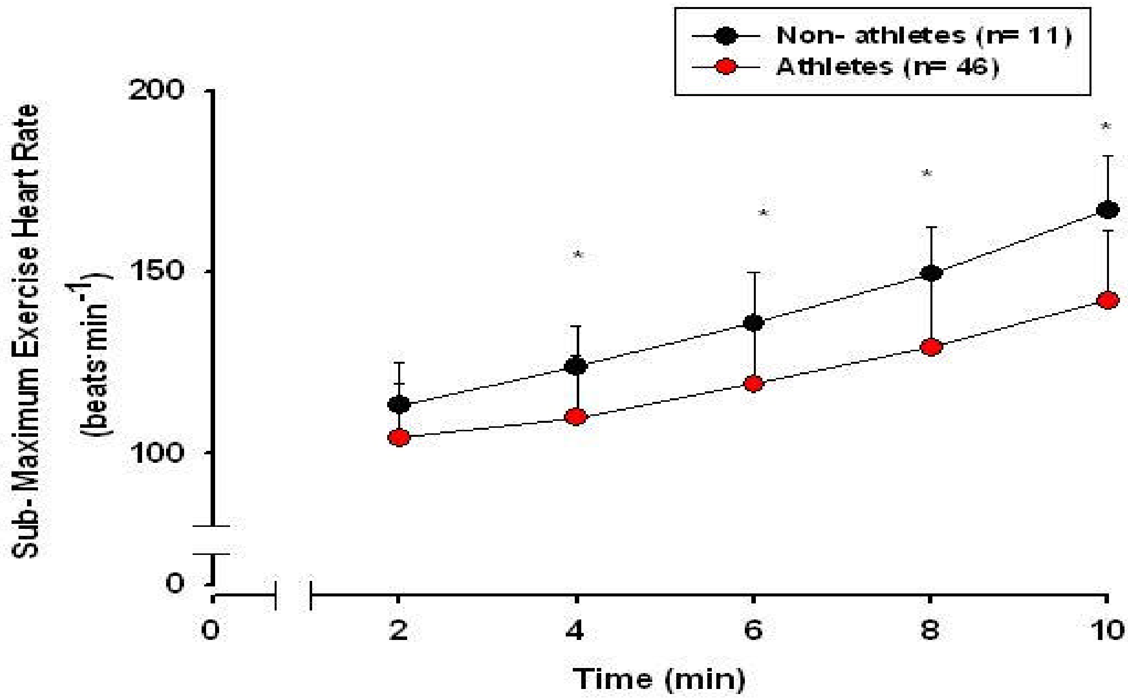

Figure 3. Sub-maximal exercise HR (beats·min^{-1}). The symbols are the mean and its vertical line is the SEM. *Significant difference determined by means of one-way ANOVA and the *post hoc* Tukey (F_{index} = 26.8, P<0.05).

SV

It is clear from the findings that the determinant of the cardiovascular response to exercise is related to different types of training. Efforts to understand the limiting factors for physiologic aerobic fitness were directed toward characterizing the central determinants of blood flow. The submaximal exercise SV is greater in the group of athletes versus non-athletes. This finding is a function of the athletes having greater maximal ergometric power, index of maximum ergometric power (12), which is highly related to the absolute and relative VO_2 max values (4,22). The athletes with the higher VO_2 max values had higher SV values. It is more than reasonable to expect that the athletes' SV response is a culmination of an increase in the skeletal muscle pump during exercise, which increased venous return, diastolic filling, and end-diastolic volume (21). Overall, the athletes' VO_2 max was therefore significant higher than the non-athletes. In addition, the acknowledged larger heart size of endurance athletes and the faster cardiac output kinetics compared to non-athletes resulted in more oxygen delivered to and used by the peripheral tissues (28). The cardiovascular system of non-athletes is challenged by a bout of sustained exercise to increase SV to match the increase in metabolic needs of contracting skeletal muscles.

SV ANALYSIS *post hoc* BETWEEN VO_2 maxRel GROUPS

Examining differences in VO_2 max among athletes of different sports in the present study centered primarily on exercise SV. Endurance trained athletes versus athletes in sports of short duration and maximal intensity were expected to demonstrate significantly different SV values during exercise. However, SV was not significantly different between athletes of different VO_2 maxRel groups, which appear to be the result of a larger peripheral adjustment in the supply of oxygen to the exercising muscles. This point is interesting in that there is research evidence indicating that peripheral factors, particularly arteriolar dilatation and skeletal muscle pump function, control circulatory responses to exercise rather than central cardiac mechanisms (6,18).

While the focus on VO_2 maxRel is important when analyzing the component parts of cardiac function during exercise, the process itself does not always identify the limiting factor or factors. While VO_2 max explains the superior aerobic fitness in the highly trained distance runner (2,5), and while VO_2 maxRel was significantly different among the five different sport groups, the exercise SV of Mexican athletes of different sports was not significantly different. This finding seems to indicate that the athletes' training in different sports did not produce central adaptations (19) in the same proportion to the peripheral adaptations in terms of skeletal muscle capillaries, blood flow, and energy metabolism (22,31). Hence, restricting the focus to the heart as the determinant of VO_2 max and athletic success may not always be appropriate.

It should be recognized that the foregoing discussion reflects analysis of central factors only. The analysis of peripheral factors of the Mexican athletes were not evaluated, especially the known increases in the concentration of capillaries, enzymes of the aerobic metabolism (particularly that of oxidizing lipids), and the degree to which different athletic training influences mitochondria (16,22). The myriad of components responsible for circulatory flow and oxygen delivery (15) that limited the blood supply to the contracting muscles also speaks to the increased importance of peripheral extraction of oxygen at the cell level (20).

CONCLUSIONS

The estimation of SV at submaximal exercise (i.e., SV) provided the opportunity to distinguish the difference in the volume of blood pumped per beat (SV) between athletes and non-athletes, but it did not allow for further analysis between groups of athletes at different maximal aerobic power relative to their total body mass. If there are differences in SV between athletes of different sports and VO_2 maxRel values, then, the use of a recognized method such as the CO_2 rebreathing procedure to determine SV versus using a regression equation may be necessary.

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