Effect of static and dynamic exercise on heart rate and blood pressure variabilities

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ABSTRACT

GONZÁLEZ-CAMARENA, R., S. CARRASCO-SOSA, R. ROMÁN-RAMOS, M. J. GAITÁN-GONZÁLEZ, V. MEDINA-BAÑUELOS, and J. AZPIROZ-LEEHAN. Effect of static and dynamic exercise on heart rate and blood pressure variabilities. *Med. Sci. Sports Exerc.*, Vol. 32, No. 10, pp. 1719–1728, 2000. **Purpose:** This study examines the effect of static and dynamic leg exercises on heart rate variability (HRV) and blood pressure variability (BPV) in humans. **Methods:** 10 healthy male subjects were studied at rest, during static exercise performed at 30% of maximal voluntary contraction (SX30), and during dynamic cycling exercises done at 30% of $\dot{V}O_{2max}$ (DX30) and at 60% of $\dot{V}O_{2max}$ (DX60). Respiration, heart rate, and blood pressure signals were digitized to analyze temporal and spectral parameters involving short and overall indexes (SD, ΔRANGE, RMSSD, Total power), power of the low (LF), middle (MF), and high (HF) frequency components, and the baroreceptor sensitivity by the α_{MF} index. **Results:** During SX30, indexes of HRV as SD, ΔRANGE, Total power, and MF in absolute units increased in relation with rest values and were significantly higher ($P < 0.001$) than during DX30 and DX60; HF during SX30, in normalized and absolute units, was not different of the rest condition but was higher ($P < 0.001$) than HF during DX30 and DX60. Parameters of BPV as SD and ΔRANGE increased ($P < 0.001$) during both type of exercises, and significant ($P < 0.01$) increments were observed on MF during SX30 and DX30; systolic HF was attenuated during DX30 ($P < 0.05$), whereas diastolic HF was augmented during DX60 ($P < 0.001$). Compared with rest condition, the α_{MF} index decreased ($P < 0.01$) only during dynamic exercises. **Conclusion:** Because HRV and BPV response is different when induced by static or dynamic exercise, differences in the autonomic activity can be advised. Instead of the vagal withdrawal and sympathetic augmentation observed during dynamic exercise, the increase in the overall HRV and the MF component during static exercise suggest an increased activity of both autonomic branches. **Key Words:** SPECTRAL ANALYSIS, BARORECEPTOR SENSITIVITY, CARDIOVASCULAR CONTROL, AUTONOMIC ACTIVITY

The pressor and cardioacceleratory responses to exercise, noted during static and dynamic exercises, respectively, are intimately dependent of autonomic reflexes that control cardiovascular effectors. The level of autonomic activity depends on feedback mechanisms, which sense the hemodynamic conditions to adjust the offer according to the metabolic demand of the working muscles. As part of these adjustments, the heart rate (HR) and the arterial blood pressure (BP) fluctuate in a beat-to-beat mode, known as heart rate variability (HRV) and blood pressure variability (BPV), respectively. Pioneer studies based on spectral analysis have suggested that such fluctuations can be divided into frequency bands closely related to sympathetic and vagal modulation (1,19,23); those frequency bands scattered below 0.15 Hz (low frequency, LF, and middle frequency, MF), and that over 0.15 Hz (high frequency, HF).

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Several studies have been done on spectral analysis of cardiovascular fluctuations during dynamic exercise, and although they have brought some interpretative controversies about the physiological meaning of specific spectral bands (7,34), the general image on HRV is consistent with a reduction of the total power in all frequency bands (2,3,10,14,22,25,35). For most of the authors, the power of these frequency bands, and especially when they are expressed in normalized units, substantiated the general scheme of vagal withdrawal and sympathetic activation during light or moderate dynamic exercise (3,10,14,25,35), first described by Robinson et al. in 1966 (27). On the other hand, the total power of systolic blood pressure variability (SBPV) increases during dynamic exercise (8,14,25), whereas LF power goes up (25) or LF power did not change while HF power increases (8,14).

Despite that the same sequence of vagal withdrawal and sympathetic activation has been described during static exercise after pharmacological blockade (13,15), different autonomic responses between static and dynamic exercises have also been proposed (29). However, by using spectral analysis of the HRV, a nonsignificant difference has been reported between light static versus rhythmic handgrip (11), but it has also been referred that, compared with rhythmic handgrip, sustained moderate handgrip elicits a higher relative LF component (18). Because this last study has been reported with no methodological details, whether or not during static exercise the spectral analysis of HRV and BPV resembles the behavior observed during dynamic activity remains unclear.

The purpose of the present study was to explore by means of spectral analysis possible differences on the HRV and BPV responses to static and dynamic leg exercises in healthy subjects. To accomplish this, the HRV and BPV responses to these types of exercises were first compared at matched relative workloads, thereafter at matched mean blood pressures.

MATERIALS AND METHODS

Subjects. Ten male volunteers (20–27 yr old) were recruited at the Laboratory of Human Physiology of the Metropolitan Autonomous University, in Mexico City. The healthy status of the volunteers was tested by means of an extensive clinical history, together with standard 12-lead ECG at rest and spirometry. Only sedentary, nonsmoking subjects without clinical evidence of endocrine, cardiac, or respiratory disorders were chosen for the purpose of this study. Finally, they were added as participants, after signing an informed consent.

Study design. The study was designed to evaluate the response of heart rate and blood pressure variabilities when stimulation by static or dynamic exercise was applied at steady state conditions. Therefore, to facilitate the selection of the relative loads given to the subjects on the experimental protocol, they underwent preliminary tests, first for maximal voluntary contraction (MVC) and over 2 d later for maximal oxygen uptake ($\dot{V}O_{2max}$). Finally, within 1 wk of the preliminary tests, subjects returned to the laboratory to complete a set of submaximal static and dynamic protocols for HRV and BPV studies.

Maximal preliminary tests. MVC was tested on a training apparatus by extension of both knees against a weight, with the subject seated and without arm support. Verbal instructions were given to all subjects during the maximal contraction to use only the quadriceps femoris muscle of both legs and to keep muscles of the arms and torso relaxed. Maximal contraction (in kg) was considered the highest value of three to six tries. Each try lasted 2–3 s and resting periods of 3–5 min were left between tries.

$\dot{V}O_{2max}$ test was performed on a cycle ergometer (Monark 818E, Varberg, Sweden) based on a protocol with incremental loads of 25 W each minute. During a testing session, 20-s values of pulmonary ventilation, oxygen consumption, carbon dioxide production, and respiratory exchange ratio were computed. The major components of the gas analysis system were a Hewlett-Packard pneumotach package, a Beckman OM-11 oxygen analyzer, a Beckman LB-2 carbon dioxide analyzer, and a PC with A/D converter and specific software. The gas analyzers were calibrated with calibration gases and the pneumotach was calibrated with repeated pumps from a 3-L syringe. The criterion for $\dot{V}O_{2max}$ was achieving two of the following three conditions: 1) plateau or increase of $\leq$ 2.0 mL·kg^{-1}·min^{-1} over two consecutive stages of increasing work, 2) heart rate $\geq$ 90% of age-predicted maximum, and 3) respiratory exchange ratio value $\geq$ 1.1.

TABLE 1. Physical and functional characteristics of the studied subjects (N = 10).

Variable	Mean ± SD
Age (yr)	23.9 ± 2.41
Weight (kg)	62.8 ± 6.11
Height (cm)	163.7 ± 5.23
Body surface (m^2)	1.690 ± 0.09
HR_{max} (beats·min^{-1})	193.3 ± 12.1
$\dot{V}O_{2max}$ (mL·min^{-1}·kg^{-1})	42.7 ± 4.7
MVC (kg)	60.8 ± 7.6

HR_{max}, maximal heart rate; $\dot{V}O_{2max}$, maximal oxygen uptake; MVC, maximal voluntary contraction.

Continuous monitoring of the ECG (Hewlett-Packard 78330A monitor) was maintained by means of a CM5 lead during maximal exercise tests. Table 1 summarizes the average physical characteristics of the volunteers studied, including their $\dot{V}O_{2max}$, maximal HR at $\dot{V}O_{2max}$, and MVC values.

Static and dynamic exercise protocols. To attenuate the possibility of an altered autonomic balance, participants were requested to keep a resting period the night before the study and to avoid any drug, coffee, or fatiguing physical activity at least 24 h before the study. Also, they were clinically free of signs and symptoms of any acute disease on the day of study. The subjects fasting for at least 3 h entered at the laboratory around 9:00 a.m., according to their respective appointments.

After testing the rest condition, volunteers followed either static or dynamic exercises whose order was arranged to create a balanced design. Rest condition was tested during 10–15 min, while subjects stood seated and gently tied to a chair with a wide belt around the abdomen. Also at the sitting position, static exercise was performed at 30% of MVC (SX30) by holding isometric contractions of both quadriceps femoris muscles against a weight sustained in between of the left and right medial malleolus of the ankles. This contraction caused the knee extension from 90° to 170°, which was kept up for 6 min. The subjects were encouraged to uphold their legs extended, refraining from any arm contraction, and to hold an open glottis to avoid the Valsalva maneuver. Dynamic conditions were tested at 30% of $\dot{V}O_{2max}$ (DX30), to match the relative intensity of SX30 (5), and at 60% of $\dot{V}O_{2max}$ (DX60), to match as close as possible the SX30 mean blood pressure (5), while the subjects, seated on a cycle ergometer, were pedaling at 60 rpm for six min.

At the end of each exercise, the subjects were questioned about their fatigue feelings, according to the Borg's scale for rating perceived exertion. A recovery period of 10–15 min was left between exercises, until HR and BP returned to rest values.

For each test condition, ECG, instantaneous HR, indirect BP, and respiratory cycle (RESP) were continuously mon-

TABLE 2. Responses (mean ± SD) at rest and during the types of exercise ($N = 10$).

Variable	REST	SX30	DX30	DX60
Heart rate (beats·min^{-1})	61.9 ± 8.3	84.1 ± 9.1* † §	93.7 ± 8.6* §	143.9 ± 9.1*
Systolic blood pressure (mm Hg)	121.6 ± 7.8	166.7 ± 15.5* †	150.8 ± 12.3* §	173.9 ± 14.6*
Mean blood pressure (mm Hg)	91.2 ± 5.8	122.2 ± 11.7* †	107.7 ± 8.1* §	121.6 ± 12.6*
Diastolic blood pressure (mm Hg)	76.4 ± 4.6	100.8 ± 11.1* †	86.7 ± 7.8* §	97.7 ± 12.1*
Respiratory rate (breaths·min^{-1})	17.9 ± 5.1	21.9 ± 5.7* §	23.4 ± 6.1* §	34.8 ± 7.7*

SX30, static exercise at 30% of maximal voluntary contraction; DX30, dynamic exercise at 30% of $\dot{V}O_{2max}$; DX60, dynamic exercise at 60% of VO_{2max}.
* Significant differences ($P < 0.05$), compared with REST.
† Significant differences ($P < 0.05$), compared with DX30.
§ Significant differences ($P < 0.05$), compared with DX60.

itored. To record the ECG and the instantaneous HR, the CM5 electrocardiographic lead was processed through a monitor (Hewlett-Packard 78330A) and a rate computer (Hewlett Packard 8812A) with precision over 1 ms. Indirect BP wave was recorded from the index finger of the right hand via an optico-mechanical plethysmographic system (Finapres, Ohmeda-2300, Inc., Denver, CO), after patent ulnar and radial arteries were confirmed by the radial compression test of Allen. In all conditions, the right forearm and the hand were maintained horizontal and at a constant height, at the level of the fifth intercostal space, with the aid of a supporter. Extreme care was taken to insist that contractions of superior limbs were avoided. RESP was obtained from a sensor strap (Pro-Tech Services, Inc., Woodinville, WA) placed around the thorax. The sensor signal, based on a piezoelectric crystal transducer, was amplified and low-pass filtered at 30 Hz (Narco Bio-Systems Inc., Austin, TX).

Signal processing. Analog signals of instantaneous HR, indirect BP, and RESP were digitized in a PC by means of a 12-bit A/D converter (Advantech Corp., Sunnyvale, CA), at a sample rate of 100 Hz. The indirect BP signal was processed to detect beat-to-beat systolic and diastolic blood pressures, and to compute the mean blood pressure. Values for systolic blood pressure (SBP) were defined as the highest peaks of pulse waves, whereas values for diastolic blood pressure (DBP) were identified as the points of minimum intensity closer to the upstroke of the pulse waves. Mean blood pressure (MBP) was computed as the integral of the pulse waves. Finally, the time series of HR, SBP, DBP, and RESP were evenly resampled at 2 Hz after cubic spline interpolation. However, to approach the analysis under steady state conditions, only the last 512 points of the time series were processed. Stationarity of a time series was considered when the mean and the spectral power difference between the two halves of a series were <5% (19).

Time domain measures. Parameters measured on HR and BP records, as part of the time domain analysis, included the mean, the standard deviation (SD), the difference between the highest and the lowest value (ΔRANGE), and the square root of the mean of the sum of the squares of differences between adjacent values (RMSSD). The temporal parameters SD and ΔRANGE were considered estimators of the overall long-term variability while RMSSD was of the beat-to-beat variability (33).

Frequency domain measures. The frequency domain analysis of the linearly detrended series was based in the estimation of the power spectral density by Welch's averaged periodogram method using Hanning windows of size 128, with an overlapping of 64 points.

Parameters obtained from the spectral estimation of HRV and BPV were, a) total power (Ptot, up to 0.4 Hz), b) low frequency power (LF, 0.04–0.07 Hz) in absolute and normalized units, c) mid-frequency power (MF, 0.07–0.15 Hz) in absolute and normalized units, and d) high frequency power (HF, 0.15–0.4 Hz) in absolute and normalized units (21,33). The spectral components considered as low frequencies (LF and MF) were added to get the low over high frequency ratio ((LF+MF)/HF). In case of respiratory signals, instead of getting spectral parameters, their spectral power densities were used to compute the coherence with respect to HRV and SBPV spectral power densities. Coherence values higher than 0.5 indicated the frequency band where significant linear correlation existed between the frequency components of the signals.

An α_{MF} index in the range of 0.07 to 0.15 Hz was used to assess the spontaneous baroreceptor sensitivity during static and dynamic exercises. In brief, this index was calculated as the square root of the HRV power over SBPV power ratio, provided that in the range of 0.07 to 0.15 Hz the coherence between the power spectral densities for HRV and SBPV was more than 0.5 (20,26).

Statistical analysis. For each parameter in the time and frequency domains, the averages and standard deviations were obtained to test statistical differences. The frequency domain parameters were normalized by logarithmic transformation whenever a skewed distribution was found. Comparisons were done by a repeated-measures one-way analysis of variance among the conditions that were explored (rest, SX30, DX30, and DX60) followed by *post hoc* Tukey's test to pinpoint differences. For all hypothesis test, $P < 0.05$ was considered statistically significant.

RESULTS

Although during the last min of SX30 all subjects noted leg discomfort and the effort perception scored from 9 to 10, they were able to sustain the 30% of MVC contraction until the records were completed. Conversely, despite the relative intensity of dynamic exercises was equal (30% of $\dot{V}O_{2max}$) or two-fold (60% of $\dot{V}O_{2max}$), the volunteers felt lighter the dynamic loads (3–5 and 5–7 scores, respectively) than the SX30 load.

Table 2 depicts the means and standard deviations of heart rate, mean blood pressure, and respiration at rest and during the different type of exercises. SX30 showed small increases in mean HR but was significantly higher than the HR at rest. In comparison also with rest values, HR during dynamic exercises showed more substantial increases, so that these means were statistically higher than the mean HR during SX30.

The mean blood pressure increased during the two types of exercise when compared with rest values. The mean blood pressures were statistically similar for SX30 and DX60, and these both were higher ($P < 0.001$) than for DX30.

The respiratory rate increased during SX30, DX30, and DX60, compared with rest values. The mean increment in the respiratory rate under SX30 condition was alike to the mean of DX30 and significantly lower ($P < 0.001$) than the mean of DX60.

Effects of exercise on time domain measures of HRV and BPV. The response of time domain parameters for HRV, SBPV, and DBPV to static and dynamic exercises is presented as mean values in Figure 1. All HR time series accomplished the steady state condition, because the stationarity value was below 3%. Nevertheless, in case of static exercise, the DBP and more so the SBP held a slow upward trend, whereas during dynamic exercises the trend of the blood pressure time series was downward. Such trends in blood pressure were high enough to cause that four subjects during static exercise and three subjects during dynamic exercise presented a difference around 6% between the mean of the two halves of the diastolic and systolic time series.

At SX30 the means of SD and ΔRANGE parameters for HRV increased significantly from rest values, whereas the change in RMSSD did not reach statistical significance. In case of dynamic exercises, at DX30 the time domain indexes tended to remain unchanged except ΔRANGE, which showed a small but significant increase. When exercising at 60% of $\dot{V}O_{2max}$, a clear decline was observed on the three indexes. Contrasts among exercises remarked that SX30 got significantly higher SD, ΔRANGE, and RMSSD values than DX60, and higher SD, and RMSSD values than DX30 ($P < 0.001$).

During both static and dynamic activities, and for SBPV and DBPV, the temporal parameters SD and the ΔRANGE increased from rest values. The other parameter, RMSSD, for SBPV and DBPV, was unaltered during SX30, whereas it significantly augmented during DX60. RMSSD during DX30 augmented only for DBPV. Differences between exercises showed that SD, ΔRANGE, and RMSSD values were lower for SX30 than for DX60 ($P < 0.001$). Significant differences between SX30 and DX30 were only proved for RMSSD at DBPV as lower values were seen during SX30 ($P < 0.001$).

Effects of exercise on frequency domain measures of HRV. Figure 2 displays a typical example of HR and SBP time series and their respective power spectral densities during rest and the two types of exercise. Figure 3

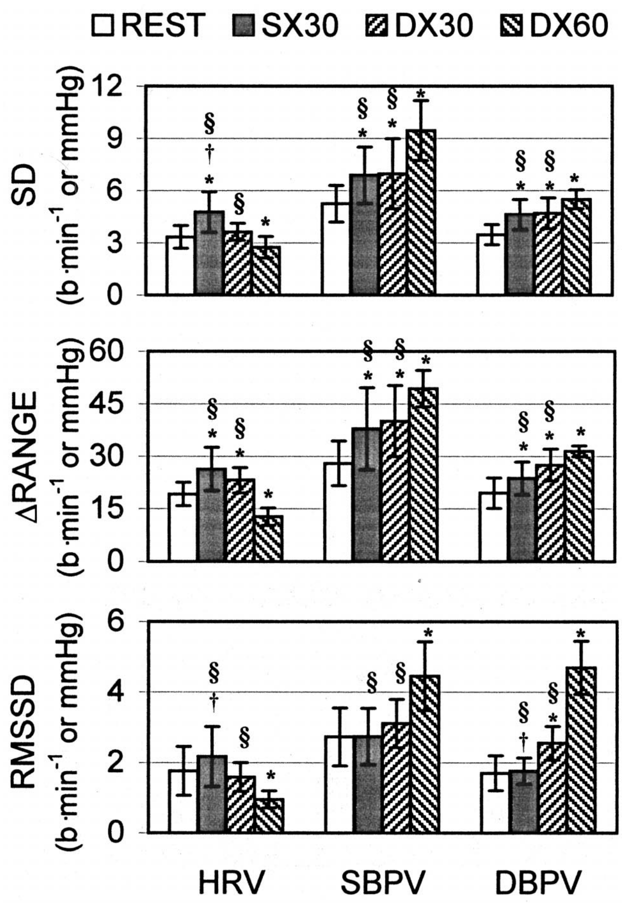

Figure 1—Effects of static exercise, at 30% of maximal voluntary contraction (SX30), and dynamic exercises, at 30% of $\dot{V}O_{2max}$ (DX30) and at 60% of $\dot{V}O_{2max}$ (DX60), on temporal parameters of heart rate variability (HRV), systolic blood pressure variability, and diastolic blood pressure variability (DBPV). The *bars* display the mean and standard deviation of each temporal parameter. Other abbreviations and symbols were as follow: SD, mean of standard deviations; ΔRANGE, mean of the differences between maximal and minimal data; RMSSD, mean of square roots of the mean of the sum of the squares of differences between adjacent data; * significant differences ($P < 0.05$) compared with REST; † significant differences ($P < 0.05$) compared with DX30; § significant differences ($P < 0.05$) compared with DX60.

shows graphically the means and standard deviations of the spectral components of the HRV.

Comparisons between each kind of exercise against rest mean values revealed that at SX30 Ptot increased around 88.6%, whereas at dynamic exercises it significantly decreased around 14.5% during DX30, and 73.2% during DX60. There were significant differences ($P < 0.001$) on Ptot among the three types of exercise, being SX30 the highest and DX60 the lowest.

During SX30, the spectral analysis indicated that the augmentation on Ptot was unevenly distributed along the specific frequency components. For example, and compared with rest values, in absolute units the LF+MF power significantly increased ($P < 0.001$) at the expense of the MF increment ($P < 0.001$) but LF did not change. In normalized units, LF+MF showed a nonsignificant change with respect to rest values; however, the LF component presented a significant decrement ($P < 0.001$), whereas the MF com-

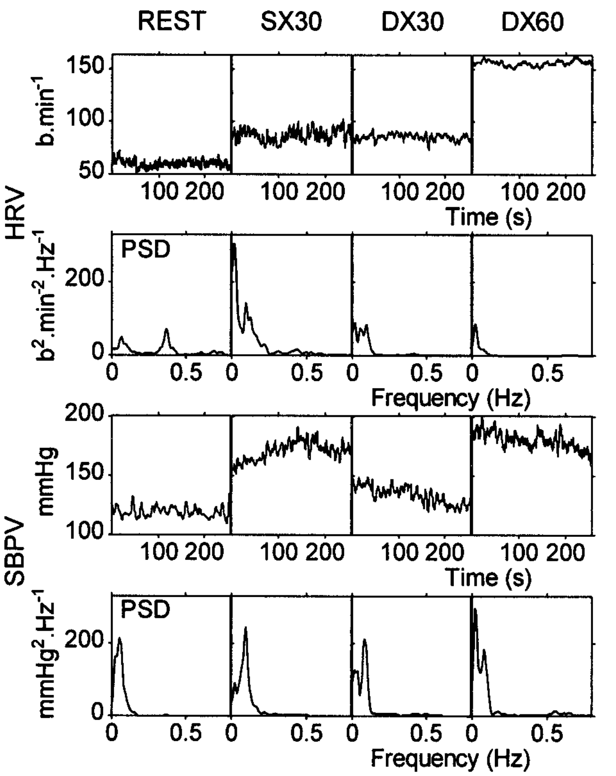

Figure 2—One subject example of the time series and the power spectral densities (PSD) of heart rate variability (HRV) and systolic blood pressure variability (SBPV) during rest, static exercise at 30% of maximal voluntary contraction (SX30), dynamic exercise at 30% of $\dot{V}O_{2max}$ (DX30), and dynamic exercise at 60% of $\dot{V}O_{2max}$ (DX60). Note the same scales and the higher area of PSD in HRV during the static exercise.

ponent a significant increment ($P < 0.002$). Finally, although the normalized HF values tended downward, the change was statistically nonimportant.

In regard to dynamic exercise, in terms of absolute values and compared with rest conditions, DX30 was characterized by unvarying LF+MF and MF power, a small but significant decrement in the LF power ($P < 0.05$), and a more clear reduction in the HF power ($P < 0.01$). On the same terms, DX60 showed a marked decrease in the power of all spectral components ($P < 0.001$). In terms of normalized units, the LF+MF component presented significant increases ($P < 0.001$) from rest values for both DX30 and DX60. The increment noticed in normalized LF+MF during DX30 was dependent on the change in the MF component, whereas during DX60 the increment was related to the change in LF component. The normalized HF component was significantly reduced ($P < 0.01$) for DX30 and DX60.

Comparisons among static and dynamic conditions showed that, in normalized units, the MF component during SX30 presented higher values ($P < 0.001$) than DX60, and in absolute units SX30 revealed higher power ($P < 0.001$) than dynamic exercises, DX30 and DX60. In the same way of comparison, during SX30 the normalized LF component was lower ($P < 0.01$) than during DX60, but in absolute units it was higher ($P < 0.01$). Finally, although the normalized HF component decreased in all exercise conditions the deepest decrement was seen during DX30 followed by DX60 and SX30, so that there were significant differences among SX30 and both dynamic exercises ($P < 0.001$).

Means of the (LF+MF)/HF ratio showed a tendency toward higher values during both types of exercise in comparison with rest values; however, only the spectral response to dynamic exercises, DX30 and DX60, achieved statistical significance ($P < 0.001$). On the other side, because the increase in LF+MF and the decrease in HF were more evident during dynamic exercises, their mean (LF+MF)/HF ratios were statistically significant ($P < 0.01$) when compared with those of SX30.

Effects of exercise on frequency domain measures of SBPV and DBPV. Figures 4 and 5 display the mean values of frequency domain measures for SBPV and

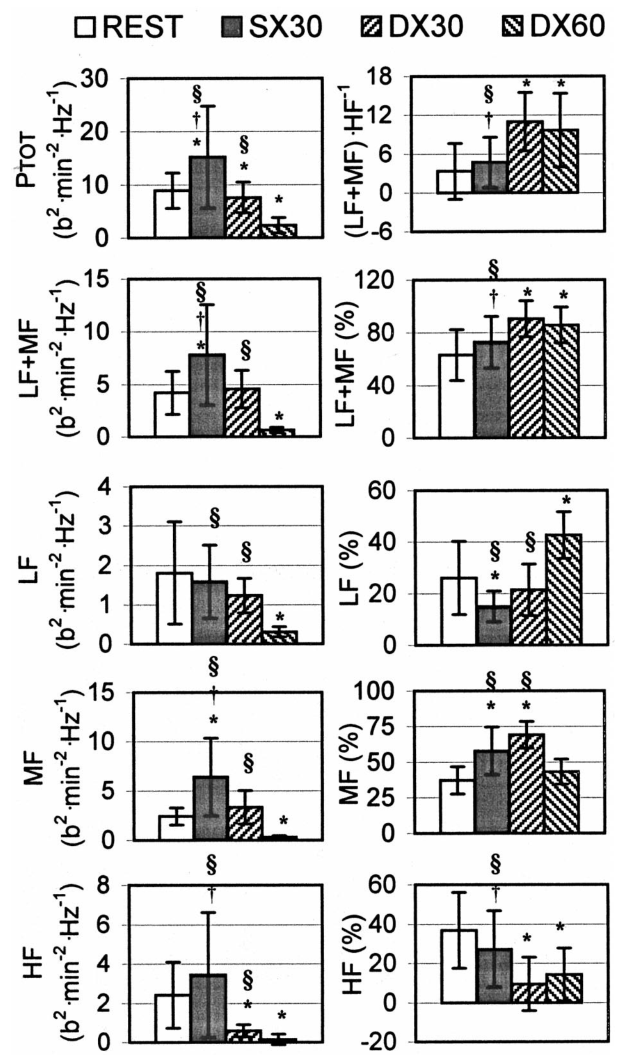

Figure 3—Effect of static exercise, at 30% of maximal voluntary contraction (SX30), and dynamic exercises, at 30% of $\dot{V}O_{2max}$ (DX30) and at 60% of $\dot{V}O_{2max}$ (DX60), on spectral parameters of heart rate variability. The *bars* display the mean and standard deviation of each spectral parameter in absolute ($beats^2 \cdot min^{-2} \cdot Hz^{-1}$) and normalized units (%). Other abbreviations and symbols were as follow: Ptot, total power; LF, power of the low frequency component; MF, power of the middle frequency component; HF, power of the high frequency component; * significant differences ($P < 0.05$) compared with REST; † significant differences ($P < 0.05$) compared with DX30; § significant differences ($P < 0.05$) compared with DX60.

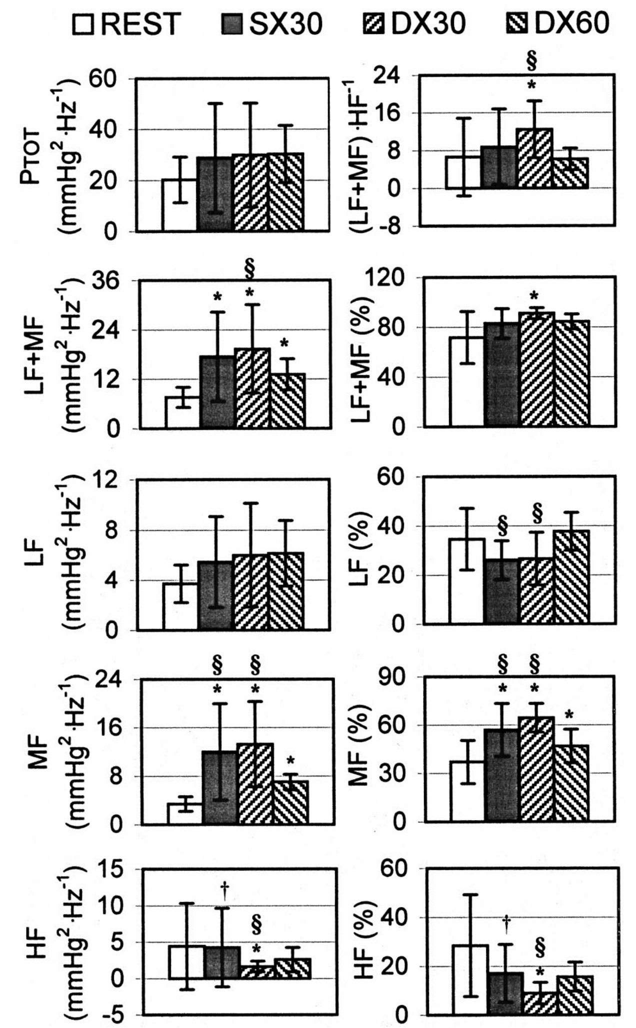

Figure 4—Effect of static exercise, at 30% of maximal voluntary contraction (SX30), and dynamic exercises, at 30% of $\dot{V}O_{2max}$ (DX30) and at 60% of $\dot{V}O_{2max}$ (DX60), on spectral parameters of systolic blood pressure variability. The *bars* display the mean and standard deviation of each spectral parameter in absolute (mm $Hg^2 \cdot Hz^{-1}$) and normalized units (%). Other abbreviations and symbols as in Figure 3.

DBPV, respectively. Ptot for systolic and diastolic spectra increased during both types of exercise, static and dynamic; however, compared with rest values, they only achieved significant difference for diastolic spectra ($P < 0.05$). There were no differences in Ptot for SBPV and DBPV among the types of exercise.

Such behavior of Ptot was reflected on the LF+MF power, because this was augmented in all types of exercise for SBPV and DBPV. However, the contribution of the specific components on Ptot pointed to a striking influence of the MF power at SX30 and DX30, whose systolic and diastolic values were higher than those of DX60 ($P < 0.01$). Compared with normalized rest values, only systolic LF+MF during DX30 showed a significant increment ($P < 0.001$), whereas diastolic LF+MF did not rise during any of the exercise conditions; even more, during DX60 this parameter decreased ($P < 0.01$).

In particular, SBPV at SX30 and DX30 presented a notable increase in the MF component, in absolute and normalized units, accompanied by unimportant changes in LF component. However, differences were seen in the HF component, for it was unaltered during SX30 and significantly decreased during DX30. On the other side, although for SBPV DX60 the MF component also increased, it showed a lower increase than SX30 and DX30, and the LF and HF components remained unmodified with respect to rest conditions. SBPV comparisons among the type of exercises indicated that the normalized LF power during SX30 and DX30 was lower than during DX60 ($P < 0.001$), that the absolute and normalized MF component during SX30 and DX30 was higher than during DX60 ($P < 0.001$), and that HF during DX30 was lower than during SX30 and DX60 ($P < 0.01$).

With respect to DBPV, the exercise spectral response was almost equivalent to that observed for SBPV; however, some remarkable differences were noted. First, MF power in absolute and normalized units at DX60 did not change with

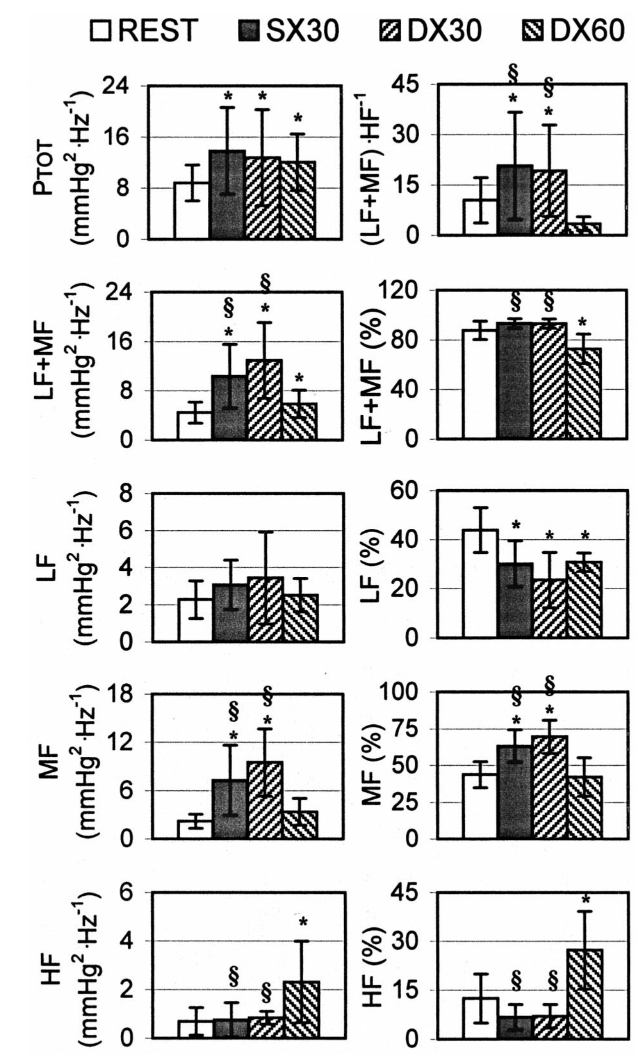

Figure 5—Effect of static exercise, at 30% of maximal voluntary contraction (SX30), and dynamic exercises, at 30% of $\dot{V}O_{2max}$ (DX30) and at 60% of $\dot{V}O_{2max}$ (DX60), on spectral parameters of diastolic blood pressure variability. The *bars* display the mean and standard deviation of each spectral parameter in absolute (mm $Hg^2 \cdot Hz^{-1}$) and normalized units (%). Other abbreviations and symbols as in Figure 3.

respect to rest conditions; second, normalized LF component at SX30, DX30, and DX60 decreased in comparison with rest values ($P < 0.01$); third, HF power in absolute and normalized units at DX30 did not change with respect to rest condition; and fourth, HF power in absolute and normalized units at DX60 was higher than any other condition ($P < 0.001$).

Finally, the trend of each spectral component of the BPV was reflected on the (LF+MF)/HF ratio. Therefore, the ratio increased in a significant way ($P < 0.05$) during systolic and diastolic DX30 and only during diastolic SX30. The diastolic (LF+MF)/HF ratios during SX30 and DX30 were higher ($P < 0.001$) than the respective ratio during DX60 ($P < 0.001$).

Coherence for HF component and respiration. The spectral power of the respiratory cycle presented a coherence higher than 0.5 with the HF component for HRV and for BPV, in all records from the resting and the three experimental conditions.

Effects of exercise on baroreceptor sensitivity. At rest, during SX30, and during DX30 the coherence between the MF band in systolic and HR spectral power was over 0.5 in all subjects. However, during DX60 such coherence declined and, although it gave mean values over 0.5, its range was from 0.10 to 0.71 along the MF band.

The α_{MF} index, in beats·min^{-1}·mm Hg^{-1}, showed differences among the explored conditions, because it was statistically lower ($P < 0.001$) for DX60 (0.206 ± 0.05) than for rest (0.787 ± 0.061), SX30 (0.727 ± 0.155), and DX30 (0.602 ± 0.148). During DX30 the index tended also to be lower; in fact, it achieved significance when compared with rest conditions, but not with SX30. The α_{MF} indexes at rest and during SX30 were not statistically different.

DISCUSSION

Even though steady static and dynamic exercises were done at the same relative work load or at the same mean blood pressure, the findings in the present study point to distinct cardiovascular beat-to-beat responses associated to the type of exercise. Actually, contrary to the depressed HRV induced by dynamic exercises, the static exercise provoked a greater HRV response, as shown by temporal and spectral measures. The response of BPV to different exercises pointed to similar increases of the temporal measures and LF+MF, and a variable trend of the HF component; however, the spectral analysis of both variabilities, HRV and BPV, revealed differences in the contribution of the LF, MF, and HF components to Ptot. Such differences between stable static and dynamic exercises seem to be associated to a complex integration of muscle metabolic afferents and baroreceptor sensitivity changes.

Perhaps, by means of spectral analysis, Sato et al. (30) were the first authors who described the autonomic nervous system modulation of the heart rate during dynamic exercise. Furlan et al. (8), in hypertensive elderly subjects, showed the first evidence of spectral analysis of systolic pressure that suggested the increased power in the low frequency band (0.03 to 0.15 Hz) during dynamic exercise as an index of the sympathetic efferent activity. However, they also observed a marked influence of the respiratory activity on the power of high frequency band (>0.15 Hz) that attenuated the relative low frequency contribution. Thereafter, by spectral analysis, other authors (2,3,10,14,22,25,35) have described the attenuation of the overall power of the HRV during dynamic exercise, while the normalized low frequencies remain dominant over the high frequency component, suggesting an increased sympathetic and attenuated parasympathetic activities.

Our results are in general agreement with these previous studies (2,3,10,14,22,25,35), because we also found a reduction of the overall HRV during dynamic exercise, a reduction that was dependent of the workload intensity. As reported for dynamic exercises, the normalized power of LF+MF increases whereas the HF component decreases and, consequently, the (LF+MF)/HF ratio is elevated in comparison with rest condition. Although in general we observed the same response, the trend of increasing the (LF+MF)/HF ratio was not sustained at DX60 (mainly due to a lesser increase of the LF+MF component and lesser decrease of the HF component). In fact, in the less intense dynamic exercise, DX30, the rise of normalized low frequencies was accompanied by elevation of the MF component with a small change in the α_{MF} index, and by significant reduction of the HF component with a small change in the respiratory rate. On the other hand, the elevated LF+MF during DX60 went with an elevation of the LF component, a reduction of the α_{MF} index, a rebound of the HF component, and a significant elevation of the respiratory rate.

It seems that most investigators have implicitly assumed that similar power spectral density of HRV is observed between static and dynamic exercise. However, our results show a thoroughly different response to static exercise, at least when compared with dynamic exercises at either the same relative intensity or the same mean blood pressure, suggesting a different balance of the modulation factors for heart rate and blood pressure. Surprisingly, static exercise occurs with higher overall variability, and nonsignificant changes in the LF+MF component, the HF component and the (LF+MF)/HF ratio, in addition to significant reduction in the LF component and marked elevation in the MF power.

When compared at equivalent relative workloads, static and dynamic exercise lead to similar respiratory rate and baroreceptor sensitivity, but static exercise leads to lower heart rate, higher blood pressure, and higher effort perception. Associated with this response, other differences occurred in some temporal and spectral parameters of HRV, inasmuch as during static exercise the SD, RMSSD, Ptot, LF+MF power, MF power, and HF power were higher, whereas in relative units LF+MF were lower and HF higher, conveying a lower (LF+MF)/HF ratio. However, for SBPV the only difference was in a lower absolute and normalized HF component during the static condition. These results are in disagreement with those of Lee et al. (11), who working at 10% of MVC during at least 30 min of handgrip did not observe any difference between sustained and rhythmic exercise. A possible explanation of our discrepancy is that they used exercise intensities that could be unable to induce a measurable autonomic mediation in response. Indeed, measured by the technique of muscle sympathetic neural discharge, Seals et al. did not detect important sympathetic response to either sustained handgrip (31) or rhythmic arm exercise (32), when exercises were done at intensities below 15% of MVC.

Other authors (18) studying handgrip at 25% of MVC mention that the overall spectral variability does not change significantly during both dynamic and static exercise, but normalized LF in HRV and LF in SBPV increase whereas HF in HRV decrease. In keeping with that study, we found the same response in the LF component, but from our results the increment in LF+MF and the decrement in HF were less evident during static exercise; besides, the static exercise induced increased overall HRV. There are some evidences that point to important differences between static arm and static leg exercise (24) on the sympathetic activation; thus, differences in either muscle mass and the active limb might explain our differences with Pagani et al. (18).

Hitherto, we underlined the difference in HRV and BPV induced by static and dynamic exercise performed at similar relative workload levels (SX30 vs DX30). However, under this condition the static exercise shows different hemodynamic responses to that observed during dynamic exercise, particularly in blood pressure (5). Therefore, in view of keeping similar mean blood pressures, we considered a more intense dynamic exercise (SX30 vs DX60). Although the HRV and the BPV responses to progressive static exercise remain unknown, in the present study we did not explore workload below or over 30% of the MVC. With the exercise conditions used in the present study, we pretended to cover three main scenarios: first, that the exercises were of a relative intensity enough to induce an autonomic response; second, that the HR and the BP could be sustained for a time enough to achieve steady state conditions; and third, that the blood pressures could be compared at equivalent mean values.

Under conditions of similar blood pressures but mismatched workloads, the differences between the HRV response to SX30 and DX60 were more clear. So, while during static exercise the heart rate and the respiratory rate were significantly lower, the baroreceptor sensitivity, the effort perception, the temporal parameters in HRV, and the absolute spectral parameters in HRV were higher. In respect to SBPV, the main difference between static and dynamic exercise was on the MF component at absolute and normalized units, whereas in regard to DBPV, differences in the HF appeared.

It is commonly accepted that the cardiovascular autonomic control during exercise implies a biphasic response characterized first by vagal withdrawal followed by sympathetic activation response that have been described for both dynamic (12,27) and static (13,15) exercises, so that after progressive increase of the exercise intensity there is a growing sympathetic dominance. However, contrary to this depressed vagal and increased sympathetic modulation, the results of the present study allow us to suggest that particularly during static exercise the cardiovascular modulation by the two autonomic branches is increased.

Recent studies provide some clues to think about a dual autonomic activation during static exercises. On that account, Batman et al. (4) reported that contrary to forearm dynamic exercise, the sympathoexcitation during forearm static exercise is dependent on engagement of muscle metabolite-sensitive afferents affecting the muscle vasomotor activity. Almost simultaneously in a study based on temporal analysis, Nishiyasu et al. (17) determined that HRV increases during activation of muscle metaboreflexes and suggested for the first time an enhanced parasympathetic tone during static exercises as consequence of the arterial baroreceptor loading. Our finding by temporal and spectral analysis of an increased overall HRV during static leg exercise is in agreement with that suggestion. Furthermore, our observation of a higher MF power during static exercise gives support to the hypothesis that low frequency oscillations (0.08–0.14 Hz) in HRV reflect the baroreflex vagal outflow in response to the increase in the sympathetic activity (9).

Clearly, this hypothesis comprises a baroreflex sensitive enough to respond to the increased mean arterial pressure (MAP) with a higher vagal outflow; however, Nishiyasu et al. (17) focused their study to the heart rate response, and they did not measure the baroreceptor sensitivity. As an index of the baroreceptor sensitivity, we found that compared with rest conditions the α_{MF} index during static exercise was unchanged, whereas during dynamic exercises the α_{MF} was significantly reduced, more so for the highest load we explored. As far as the α_{MF} during dynamic exercise is concerned, other authors using a similar method to estimate the baroreceptor sensitivity agree that the α index in the low frequency band centered at 0.1 Hz decreases with dynamic exercise (14,20).

In brief, from our point of view, the MF power during static exercise might represent first the sympathetic vasopressor response due to muscle metaboreflex activation and then the parasympathetic response generated by an effective baroreflex sensitivity. This parasympathetic response seems also reflected in the HF power whose magnitude is not attenuated during static exercise and contributes to a generalized HRV increase. The dynamic exercise, on the other side, could be interpreted as a vagal withdraw and blunted baroreflex sensitivity, with sympathetic modulation other than muscle metaboreflex (4,6,28). Therefore, during dynamic exercise the overall HRV decrease and the autonomic balance point to a sympathetic dominance, high (LF+MF)/HF ratio, which was more evident at 30% of the $\dot{V}O_{2max}$. Thereafter, when the respiratory rate surpasses 0.4 Hz and the baroreceptor sensitivity is deeply blunted, as during dynamic exercise at 60% of the $\dot{V}O_{2max}$, pitfalls ensue in the interpretation of the HRV spectral analysis, probably due to respiratory nonneural (7) or other humoral mechanisms (6).

Investigations on HRV and BPV during dynamic exercise that have used spectral analysis have reported controversial results in the response of the LF/HF ratio, which has been found decreased as a consequence of significant persistence of the HRV HF component (10) or increment of the SBPV HF component (8,14). Casadei et al. (7), based on autonomic blockade, proved that during moderate dynamic exercise an important fraction of the HF component, which is related to the respiratory sinus arrhythmia, is due to nonneural mechanisms. Hence, this component could overestimate the cardiac vagal activity during moderate or intense dynamic exercise. Breuer et al. (6), on the other side, studied the impact of circulating catecholamines on HRV during different dynamic exercise intensities performed on a cycle ergometer. They found a considerable reduction of the HRV, which was more pronounced at a HR of 150 beats·min^{-1}, when the circulating catecholamines were higher, and during additional infusion of catecholamines. Thus, they suggest a negative feedback of the circulating catecholamines on sympathetic heart control that reduce the low frequency (0.06–0.15 Hz) power and affect the low frequency to high frequency ratio as a sympathovagal marker. From the findings of the present work, the HF component in the diastolic spectra more clearly reflected the nonneural respiratory influence, and the LF and the MF components showed differential behaviors during exercises at different intensities. Therefore, according to previous reports (6,7) and our own results, the physiological interpretation of specific spectral components during exercise needs further studies.

It is pertinent to emphasize some methodological characteristics of the present study that can limit our observations. First, although the coherence between the spectra of systolic blood pressure and heart rate was higher than 0.5 in the MF band, the smaller coherence values were seen during dynamic exercise at the highest workload intensity. Second, although many authors rather prefer the RR interval as the natural choice to represent the HRV, we used the frequency representation based on a previous report (16). Third, the intention of the exercises performed by the subjects was to predominantly use the quadriceps femoralis, but we did not record neither muscle contraction nor strength; therefore, we cannot exclude variations in the exerted force and differences due to other possible added muscles. Fourth, the SBP and DBP time series were unsteady in some subjects during both exercises, static and dynamic; however, in all time series, the stationarity required for spectral analysis ensue after we applied the detrend function. Finally, the estimation of baroreceptors sensitivity by spectral analysis has been proposed and tested under diverse circumstances including dynamic exercise lasting at least 10 min (14,20), but it has not been during isometric exercise or dynamic exercises, at intensities and periods when systolic blood pressure could present nonstationarity. Nonetheless, the data from the present study state a contrasting response on the mean α_{MF} index during static and dynamic exercise at similar mean blood pressure, so that different mechanisms of cardiovascular control can be thought.

In conclusion, because temporal and spectral differences in HRV and BPV were present between static and dynamic exercises, performed at the same relative intensity of the workload (SX30 vs DX30) or the same blood pressure (SX30 vs DX60), we assume that the pattern activity of the autonomic control depends on the type of exercise. In comparison with dynamic exercise, on which the HRV is significantly reduced, the static exercise was characterized by an enhanced overall HRV and specific MF component in both HRV and BPV that might be elicited by an active metaboreflex and baroreflex response.

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