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The Effect of Whole Body Vibration on Oxygen Uptake and Electromyographic Signal of the Rectus Femoris Muscle during Static and Dynamic Squat

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ABSTRACT

Di Iorio F, Cesarelli M, Bifulco P, Fratini A, Roveda E, Ruffo M. The Effects of Whole Body Vibration on Oxygen Uptake and Electromyographic Signal of the Rectus Femoris Muscle during Static and Dynamic Squat. **JEPonline** 2012;15(5):18-31. Whole Body Vibrations consist of a vibration stimulus mechanically transferred to the body. The impact of vibration treatment on specific muscular activity, neuromuscular, and postural control has been widely studied. We investigated whole body vibration (WBV) effect on oxygen uptake and electromyographic signal of the rectus femoris muscle during static and dynamic squat. Fourteen healthy subjects performed a static and dynamic squat with and without vibration. During the vibration exercises, a significant increase was found in oxygen uptake (P=0.05), which increased by 44% during the static squat and 29.4% during the dynamic squat. Vibration increased heart rate by 11.1 ± 9.1 beats·min^{-1} during the static squat and 7.9 ± 8.3 beats·min^{-1} during the dynamic squat. No significant changes were observed in rate of perceived exertion between the exercises with and without vibration. The results indicate that the static squat with WBV produced higher neuromuscular and cardiorespiratory system activation for exercise duration ?60 sec. Otherwise, if the single bout duration was higher than 60 sec, the greater cardiorespiratory system activation was achieved during the dynamic squat with WBV while higher neuromuscular activation was still obtained with the static exercise.

Key Words: Vibration Treatment, Oxygen Consumption, Heart Rate

INTRODUCTION

When applied locally to the muscles or to the whole body, mechanical vibration is used as a stimulus for the neuromuscular system. Vibration is a mechanical oscillation and the parameters that characterize the stimulus, usually sinusoidal, are amplitude (peak to peak displacement) and frequency. A mechanical stimulus applied directly to the individual muscle or tendon causes a reflex muscle contraction called tonic vibration reflex (TVR) (7,15-17,40). The mechanical action of vibration produces rapid and small changes in the length of the complex muscle tendon. These changes are detected by primary sensory fibers of the muscle spindle (group Ia afferent neurons) that transmit a stimulus through the spinal cord directly to the same muscle, with the shortest possible delay, modulating the muscle contraction in order to oppose the length changes.

Vibratory stimulation can be applied also to the whole body by using vibrating platform with a vertical or a rotational (side-to-side alternating) direction. These two ways of applying the stimulus generate dissimilar mechanical behaviors and hence they lead to a different neuromuscular response (30). The impact of whole body vibration (WBV) treatments on muscular activity, neuromuscular, and postural control has been widely studied. The first application of vibration in this field was conducted by Nazarov, which demonstrated the efficacy of WBV in increasing muscle strength (28). Then, the effect of WBV treatments has been evaluated on subjects with different athletic conditions, age, sex, and according to different exercise protocols (1,8,11,18,27,32,43).

Other research activities showed that the vibration stimulus produced positive effects on bone mineral density (3,24,45,46) and human hormones (9,10,12,23); whereas, its positive effect on patients with Parkinson's disease is still doubtful (2,22,44). Roelants et al. (37) studied the electromyographic (EMG) responses of the rectus femoris, vastus lateralis, and vastus medialis during static squat. They showed that EMG activity was higher in the presence of vibration in all the muscle groups and in all exercises. In agreement, Abercromby and colleagues (1) analyzed electromyographic signals on subjects performing static and dynamic squat while on a vibration platform. They reported an increase in the neuromuscular activation of the muscles during WBV exercises.

Other works have analyzed the rise in specific oxygen consumption (sVO_2) in the last seconds of the exercise (34,35), when a steady-state condition is reached, to provide an estimation of the cardiorespiratory system activity. These studies are based on the assumption that the sVO_2 response is due to the increased number of muscle fibers (and thus the increased muscle activity) activated by the vibrations (27,31,38,39). In fact, Rittweger et al. (34) reported that simple standing and dynamic squats performed on a WBV platform increased sVO_2 compared to the same exercise without vibration. Later, Rittweger et al. (35) showed that the sVO_2 was increased when vibration frequency and amplitude were increased. Similarly, after monitoring sVO_2 and heart rate (HR) during and 24 hrs after a WBV exercise session and a second session without vibration (NoV), Hazell and Lemon (19) reported that sVO_2 was 23% higher during WBV training session.

However, it is important to point out that the studies presented in literature investigated WBV effects only on muscular activity by recording electromyographic signal (1,37) or on metabolic power by monitoring the sVO_2 (19,34,35) without standard protocol and using different exercise parameters. The purpose of this study was to monitor simultaneously both signals in a novel approach. We investigated the differences due to WBV effects on VO_2 and EMG between static and dynamic squat exercises. This was done to identify the better exercise characteristics for improving neuromuscular activation and progress in training efficacy. Monitoring VO_2 throughout the exercise and not just during the last seconds (sVO_2) of the exercise (34,35) allows for analyzing the curves from the

beginning of the exercise in order to find out possible differences in the sVO_2 trend and differences in how it is reached at steady-state.

METHODS

Subjects

Fourteen subjects in good health and not affected by any neurological or musculoskeletal disorder participated in this study. All subjects (11 males and 3 females) had been practicing regularly physical activity or non-competitive sports. The subjects were 22 to 31 yrs of age with mean and standard deviation, respectively, of 26.4 and 3.2 yrs. Their height was between 165 and 182 cm (171±6 cm), and their body weight was between 55 and 81 kg (68±9 kg). The experiments were conducted in accordance with the Declaration of Helsinki and all the subjects signed a written informed consent.

Exercises

Before the testing session, the subjects were familiarized with the vibration platform and squat exercises. The warm-up consisted of exercising on a bicycle ergometer at a load of 70 W for 10 min followed by stretching exercises for 5 min. All subjects wore socks without shoes. They performed a protocol of four kinds of exercise units (EU) that lasted 3 min and 30 sec. In the first two EU (Figure 1a), the subjects ran through an unloaded static (isometric) squat (knee angle at ~90°), without and with vibration (SS and SSV, respectively). In the other EU (Figure 1b), the squat exercises were dynamic (i.e., the subjects performed cyclic motions squatting between an angle of 110° and an angle of 90° of knee flexion with a rate of repetition equal to about 20 squats per minute) without and with vibration (DS and DSV, respectively). The exercises with no vibration (SS and DS) were used as control.

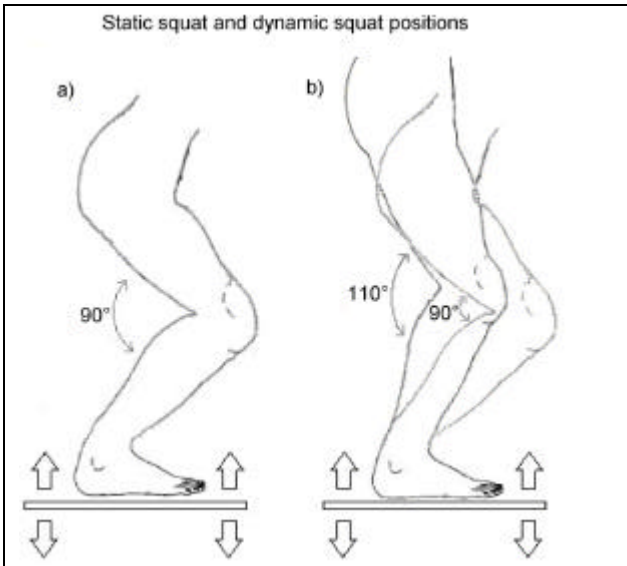

Figure 1: Static squat (a) and dynamic squat (b) positions.

Before each EU, stance of participants was monitored by checking that the distance between their heels was shoulder-width and the knee angle was evaluated by means of a goniometer. The EU sequence for each subject was randomized and between each exercise all the participants rested for about 20 min, until they felt recovered and their HR and sVO_2 signals were returned to initial values. We used CE-marked Medical Devices within the limits and according to the standard training protocols specified by the manufacturers.

Whole-body vibration treatment (WBV)

The WBV treatment was performed by using a vertical oscillating WBV platform (Vibroplate provided by TSEM SpA). The platform provided a sinusoidal vibration at a frequency of 26 Hz and a peak-to-peak displacement of 3 mm. The value of 26 Hz was chosen since it is close to the activation frequency of the quadriceps muscle group (1,8,34). The platform oscillation frequency was checked through a triaxial accelerometer based on MEMS technology placed in the platform center.

Surface EMG

Surface EMG (sEMG) signals were recorded by using small disc Ag/AgCl electrodes (diameter 5 mm) with inter-electrodes distance of 20 mm arranged in the direction of the muscle fibers, placed on the rectus femoris (RF) in accordance with the literature (20,21). In order to reduce skin impedance (<3 kO), electrode skin areas were shaved, cleaned with alcohol and a conductive gel was used. For the purpose of this study, we focused on the RF of the dominant leg (32) and reference electrode was located on the ankle of the same leg (Figure 2).

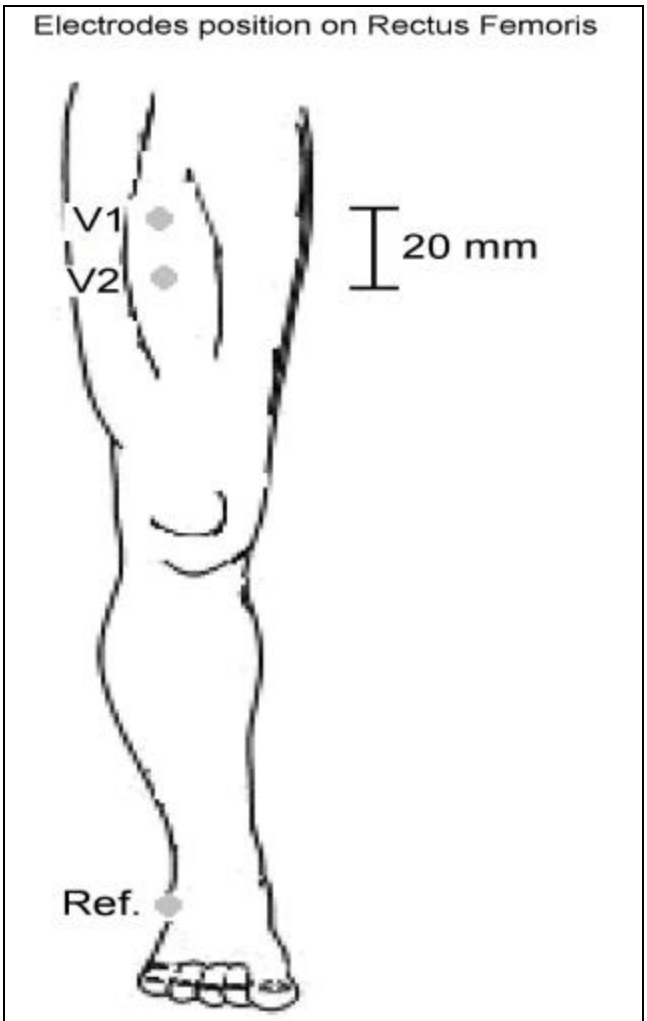

Figure 2: Electrodes position on Rectus Femoris according to SENIAM project (20,21).

The sEMG signals were amplified by using a multi-channel, isolated biomedical signal amplifier BM623 (Biomedica Magoni) with an input impedance >10 MOhm and CMRR >100 dB. The amplifier was set with a gain of 1000 V/V and a band pass filtering with cut-off frequencies of 5–500 Hz. The signals were acquired by using a PC multi-channel 16-bit data acquisition card with a sample frequency of 2048 Hz (DAQCard 6251 by National Instruments).

It is well-known that during a surface bio-potential recording, the motion artifacts that arise from relative motion between electrodes and skin result in a variation of electrodes potential. Hence, vibrations generate motion artifacts on electrodes that could be non-negligible and could affect the sEMG signals analysis (13,36). Since vibration frequency and its harmonics lie in the sEMG frequency band of 20 – 450 Hz, in order to reduce artifacts contribution, the acquired signals were processed by using sharp notch filters (band width of ±0.8 Hz) centered at the vibration frequency and its harmonics (1,13,33,41). Filters were applied to all recordings including those without vibration to ensure that loss of signal power due to the filtering procedure was the same in all recordings. Running root mean square values of the sEMG (EMGrms) were estimated by using 500 ms time window to assess muscular activity during the EU (1,13). The mean value of the EMGrms curve (mEMGrms) of each recording was computed. The mEMGrms values for the SSV and DSV were compared respectively with the controls (SS and DS), thus normalization relative to maximal voluntary contractions was unnecessary (25). Signal processing was done by using MATLAB® R2010b (The Mathworks Inc., Natick, MA).

Specific Oxygen Uptake

The subjects' oxygen uptake (VO_2) was continuously recorded by means of an oxygen consumption meter (FitMate Pro by Cosmed srl (29)) with an accuracy of ± 0.02%. Specific oxygen consumption (sVO_2) was obtained by dividing the instantaneous VO_2 by the body mass. All subjects wore FitMate Pro silicone face mask that was fitted with a head cup to prevent air leakage, and a HR chest strap; both connected to the FitMate Pro. The sVO_2 values and the HR signals were monitored continuously during the whole EU in order to analyze their trends during the exercise. To make a comparison

between the static and the dynamic squat exercises, the data acquired during the last 30 sec was used (34).

Rate of Perceived Exertion and Heart Rate

To assess the intensity of each EU, the subjects gave a rating of perceived exertion (RPE) at the end of each exercise (5,6). Resting HR was monitored before each exercise to check that the subjects recovered completely. The mean value of HR was estimated in the last 30 sec (HR_{30}) of each EU to investigate the effect of WBV on the cardio-circulatory system (4,19). In particular, estimated HR_{30} values were used to compute for each subject the increase in beats·min^{-1} (dHR_{30}) between the exercise NoV and the correspondent WBV one, according to the formula: $dHR_{30} = HR_{30WBV} - HR_{30NoV}$

Statistical Analysis

Variables, sVO_2, mEMGrms, and dHR_{30}, were tested for normal distribution with the Kolmogorov-Smirnov test (level of significance equal to 0.05) (26,42). Paired t-test was used to test differences in the sVO_2 and mEMGrms values obtained in WBV versus NoV exercises, while a one-sample t-test was performed on dHR_{30} to check the possibility of rejecting the null hypothesis (no difference in HR between exercises with WBV and NoV). Statistical significance level was set at P=0.05.
Statistical analysis was done by using the software IBM SPSS statistics 19.

RESULTS

Surface EMG

The analysis of the sEMG activity of all subjects showed that the computed EMGrms signals kept on average constant along the exercise, but their values were higher in the WBV exercises respect to the correspondent NoV (Figure 3). The mEMGrms values were normally distributed (Kolmogorov-

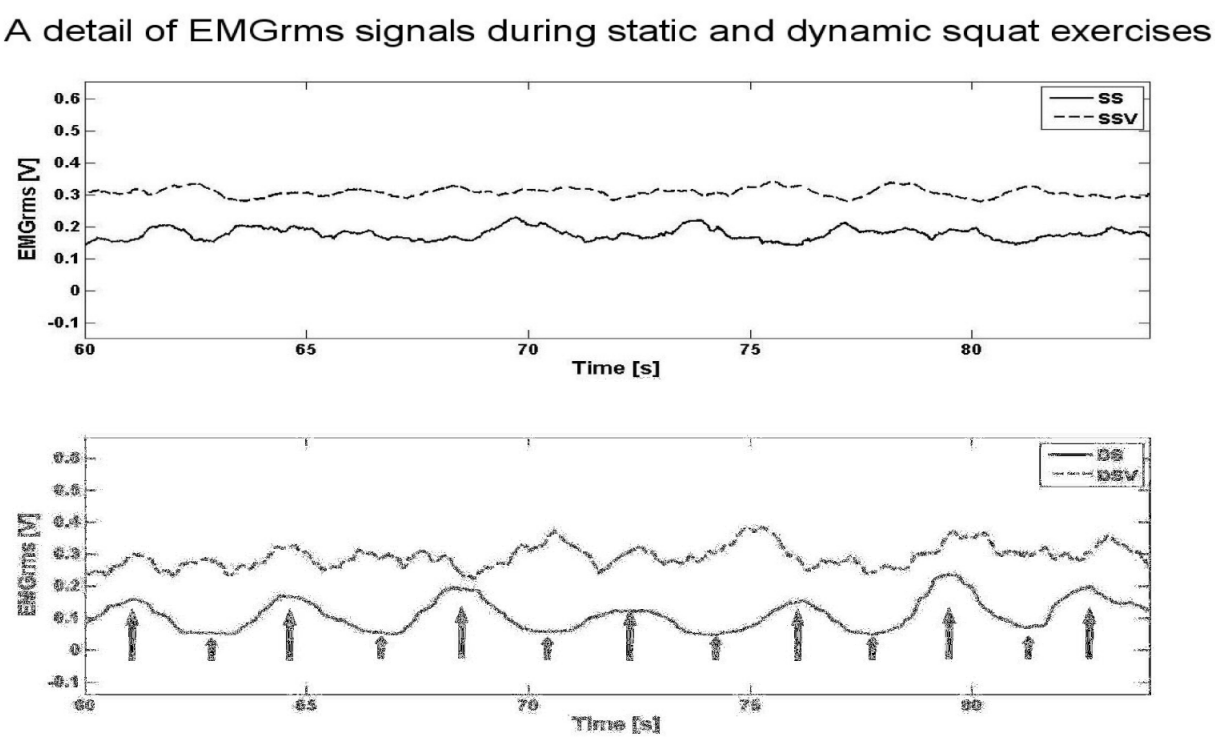

Figure 3. A detail of EMGrms signals during static (top) and dynamic (bottom) squat exercises of subject # 9. During DS exercise, EMGrms varied periodically according to the knee angle (long and short arrows in correspondence of respectively 90° and 110° angles), however its mean value holds constant.

Smirnov's test) and their means and standard deviations (Figure 4), in static and dynamic squat, indicated respectively a rise of about 63% (0.205±0.078 vs. 0.325±0.091 mV) and 108% (0.152± 0.055 vs. 0.317±0.109 mV). Paired t-test of the mEMGrms proved that the differences between WBV and NoV for both static and dynamic exercises are significant (P=0.05) showing that whole body vibration increased muscle activity.

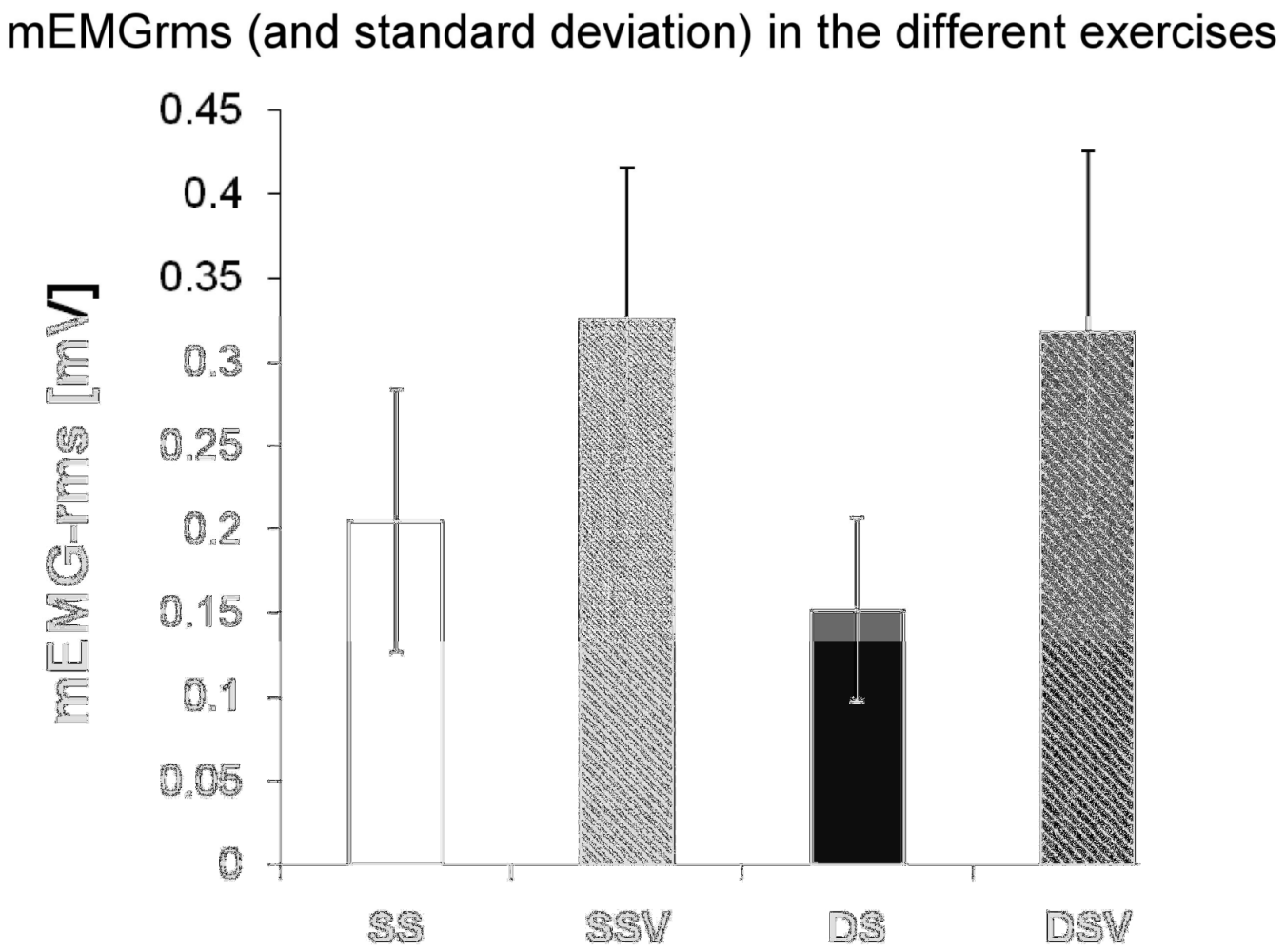

Figure 4. mEMGrms (and standard deviation) in static and dynamic exercises, with and without WBV.

Specific Oxygen Uptake

Figures 5, 6, and 7 illustrate examples of VO_2 monitored during static and dynamic exercises, with and without vibration. The WBV treatments increased the sVO_2 during the whole EU session versus the same exercise NoV, and this effect was present in all the subjects. In most of the recordings, the sVO_2 increased during the exercise up to a plateau reached approximately after the 3rd min. Thus, the mean and standard deviation of the sVO_2 values of the last 30 sec ($sVO_{2\text{-}30s}$) were chosen to compare the different EU conditions (34).

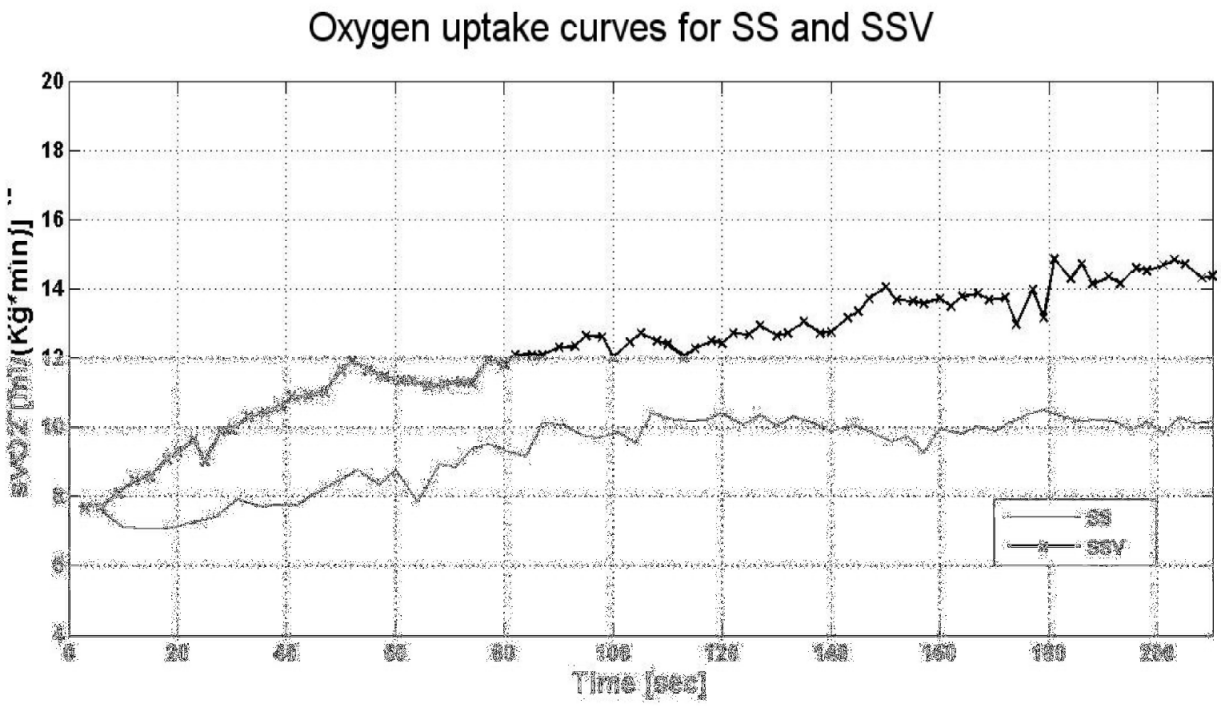

Figure 5. Oxygen uptake of subject #5 during SS and SSV. sVO_2 during SS grew for 90 sec, then it achieved a steady-state at the maximum value of 10.4 [ml·kg^{-1}·min^{-1}]. During SSV, sVO_2 increased to a maximum value of 14.9 [ml·kg^{-1}·min^{-1}].

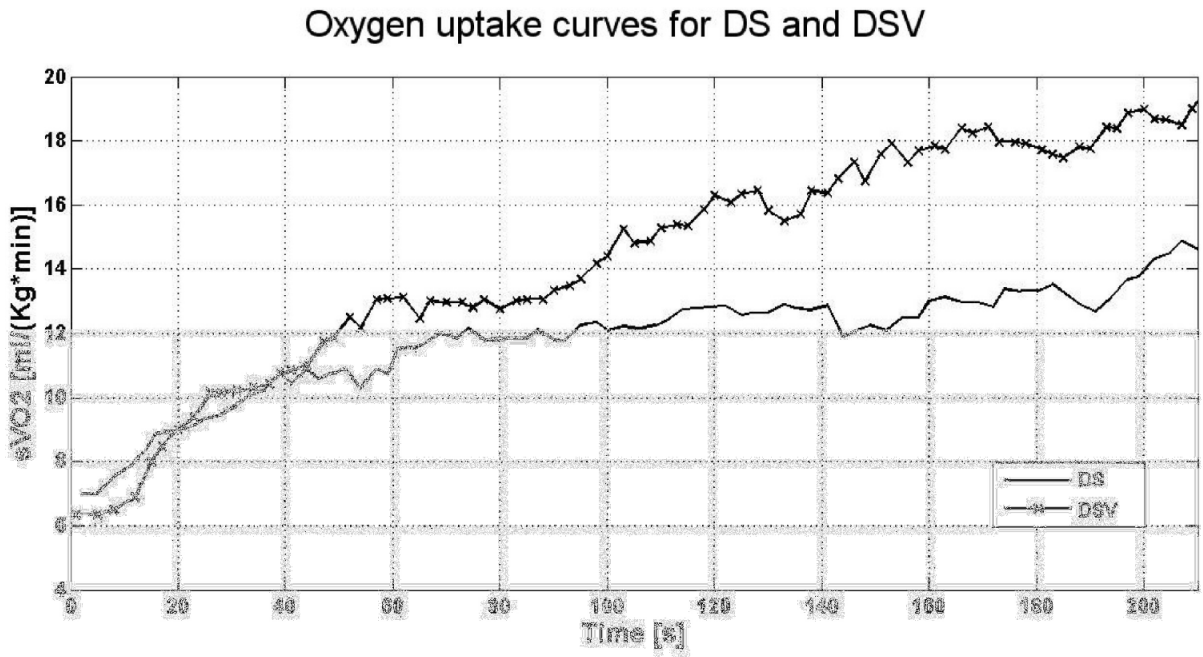

Figure 6. Oxygen uptake of subject #5; sVO_2 curves for DS and DSV show a similar pattern for the first 90 seconds and then diverge until the end. As for the static squat, sVO_2 during DS reached a plateau value around 13 [ml·kg^{-1}·min^{-1}] while sVO_2 in DSV showed an increase along the whole exercise up to a maximum value of 19.1 [ml·kg^{-1}·min^{-1}].

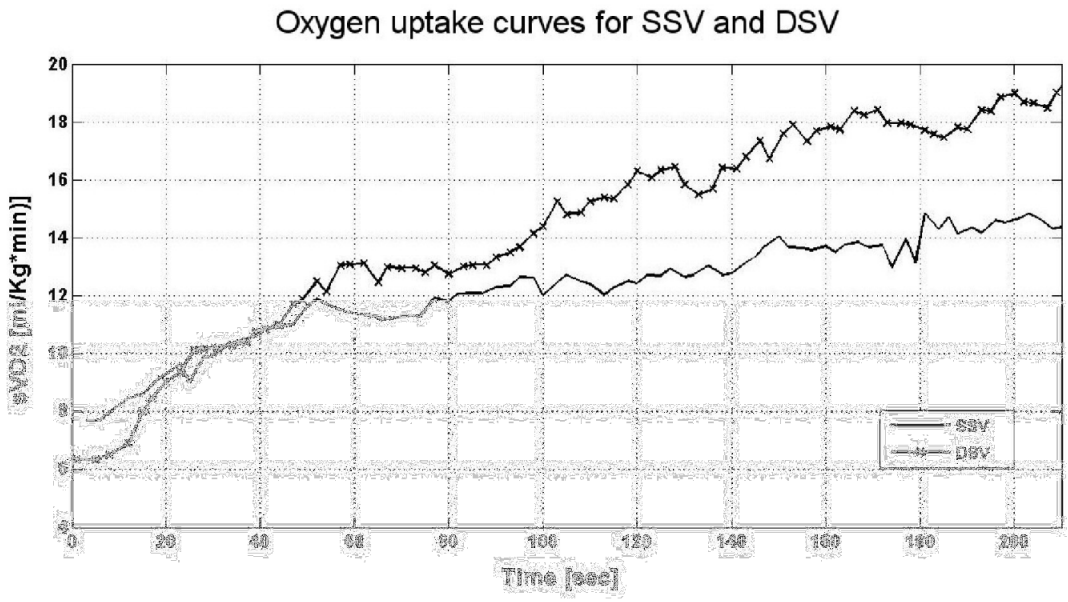

Figure 7. Oxygen uptake of subject #5; sVO_2 curves for SSV and DSV show a similar pattern for the first 50 sec and then diverge until the end, with higher values of sVO_2 in DSV.

In the majority of static squat recordings (Figure 5), for the same subject, the sVO_2 curves during SSV and SS exercises started from the same point and then diverged with different slope, higher in SSV curves. On the other hand, comparing data from DS and DSV (Figure 6) or SSV and DSV (Figure 7) exercises, sVO_2 trends were similar at the beginning and diverged significantly after about the 1st min. The $sVO_{2\text{-}30s}$ values were normally distributed and paired t-test confirmed the separation of the data over the NoV and WBV treatments in both static and dynamic EU. The WBV treatment showed a significant increase $sVO_{2\text{-}30s}$ that grew respectively of 44.0% (10.0±2.8 vs. 14.4±3.5 [$ml \cdot kg^{-1} \cdot min^{-1}$]) and 29.4% (14.3±2.7 vs. 18.5±3.9 [$ml \cdot kg^{-1} \cdot min^{-1}$]) (Figure 8).

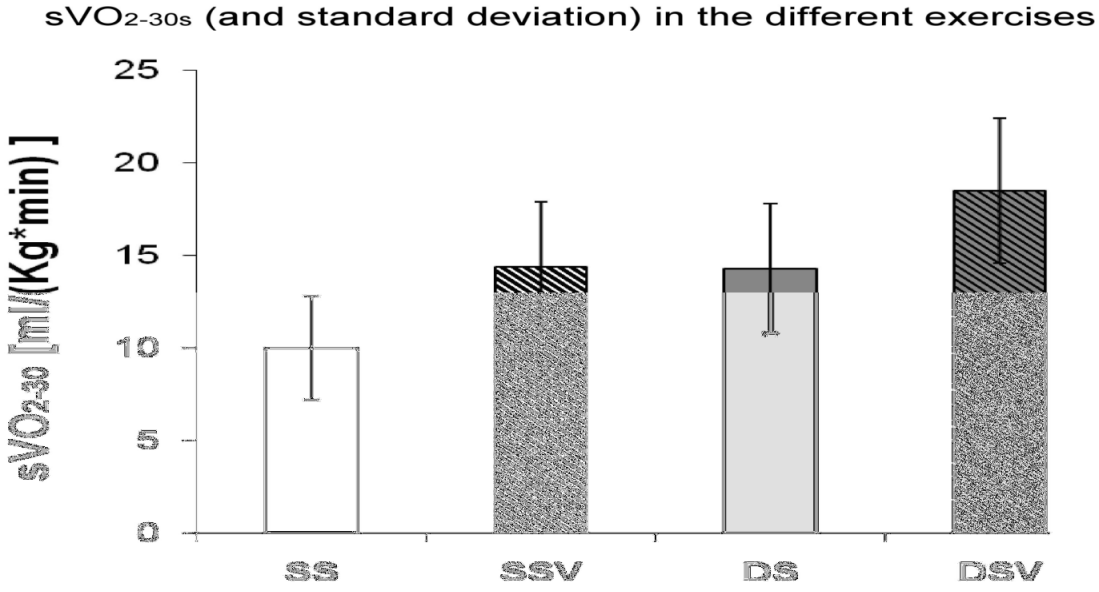

Figure 8. Mean **values with standard deviations of the $sVO_{2\text{-}30s}$ estimated for all subjects. sVO_2 increased by 44.0% in presence of vibrations during static exercise, while in dynamic exercise the increment is of 29.4%.**

Rate of Perceived Exertion and Heart Rate

Means and standard deviations for RPE during the static squat were 15.1±2.9 for NoV and 12.3±3.5 for WBV, while during the dynamic squat were 13.6±4.2 for NoV and 14.4±3.8 for WBV. No significant changes were observed between NoV and WBV exercises. However, the subjects seemed to perceive a greater effort after the static squat than the dynamic ones. The t-test results from the analysis of HR indicated that WBV treatment increased significantly the dHR_{30} for both static and dynamic squat exercises (P=0.05), showing increments respectively equal to 11.1±9.1 beats·min^{-1} for static squat and 7.9±8.3 beats·min^{-1} for dynamic squat. Summarizing, the results are shown in the following Table 1.

Table 1. T-Test Results

	NoV	WBV	p
RPE SS	15.1 ± 2.9	12.3 ± 3.5	> 0.05
RPE DS	13.6 ± 4.2	14.4 ± 3.8	> 0.05
sVO_2 SS (**ml·kg^{-1}·min^{-1}**)	10.0 ± 2.8	14.4 ± 3.5	< 0.05
sVO_2 DS (**ml·kg^{-1}·min^{-1}**)	14.3 ± 2.7	18.5 ± 3.9	< 0.05
EMGrms SS (mV)	0.205 ± 0.078	0.325 ± 0.091	< 0.05
EMGrms DS (mV)	0.152 ± 0.055	0.317 ± 0.109	< 0.05
dHR_{30} SS	11.1 ± 9.1		< 0.05
dHR_{30} DS	7.9 ± 8.3		< 0.05

The t-tests summary on 14 subjects of the studied parameters in case of NoV and WBV treatment. Means, standard deviations and p-values were reported. Only for dHR_{30} a one-sample t-test was used to test the null hypothesis that the population mean is equal to zero (no differences due to WBV).

DISCUSSION

Whole-body vibration (WBV) training was initially used in the fitness industry, but has expanded to rehabilitation, therapy, and sports. The most common effect of WBV on the muscles is the increase in strength. But, given the lack of details in the methodologies applied in various research studies, it is difficult to investigate and verify the treatment outcomes. The purpose of this study was to analyze the effects of WBV treatment on 14 healthy subjects who performed squat exercises. We evaluated the muscular activity of the rectus femoris using EMGrms parameter estimated by electromyographic signals (1,8,14,25). All signals were filtered (13,36) to reduce negligible motion artifacts due to vibrations while other signals and parameters were simultaneously taken into account. Oxygen consumption (VO_2) was used to estimate the exercise related metabolic power. Also, relative VO_2 was used to compare the VO_2 among different subjects. Heart rate and RPE provided information about the subjects' cardiac activity and the intensity of the exercise as perceived by each individual.

The main finding of this study was that WBV has the potential to increase both muscular and metabolic power, thus supporting the hypothesis that WBV has a stimulating effect on both twitch and tissue oxygenation of the muscles. In fact, our results demonstrate that estimated mEMGrms values are higher in the WBV exercises respect to the correspondent NoV of about 63% and 108% in the

static and dynamic exercises, respectively. This finding agrees with the findings of Abercromby et al. (1). They reported a significant improvement in neuromuscular activation during WBV exercises. In addition, our results indicated a higher increment of EMGrms correlated to WBV in the DSV than in the SSV.

The analysis of the NoV exercises showed that sEMG in the dynamic squat had a mean value less than the static one. This is in agreement with the observation that during the dynamic squat the twitch varies according to the knee angle. That is, since it is lower for angles >90°, the twitch in the static squat is always higher since the knee angle during the exercise is about 90°. Therefore, we hypothesized that the WBV effect would be more pronounced during the dynamic exercise, when the average of voluntary muscular contraction (not due to vibration) is lower.

Rittweger et al. (34) investigated the effect of vibration on VO_2 in different kinds of exercises. They reported incremental responses in sVO_2 with WBV treatments. Other studies are in agreement with the finding (19,35). However, it appears that no one has either monitored the sVO_2 trend during the whole exercise or compared a single bout of static and dynamic squat with WBV. In our study, monitoring the VO_2 trend since the beginning of exercises provided the opportunity to compare the slope of the curves for the different squat modalities. As a result, in general, the sVO_2 curves for the same subject during SSV and DSV were similar at the beginning and diverged significantly after about the 1st min. Consequently, WBV treatment for duration ? 60 sec, followed by a resting period, could not cause remarkable differences on oxygen uptake between static and dynamic squat. Our findings show also that the sVO_2 trend and $sVO_{2\text{-}30s}$ values were similar in SSV and DS exercises and, as a consequence, it is clear that vibration resulted in an increase in VO_2 during the static squat exercise comparable to the VO_2 obtained in the dynamic squat exercise without vibration.

The $\%HR_{30}$ results showed also an increase in the subjects' HR due to WBV of about 7.3% and 5.5% for the static and the dynamic squat exercises, respectively. Furthermore, there was no significant effect of WBV upon RPE, although values depicted a greater effort after the static exercise than the dynamic exercise. The reason of these results could lie in the nature of the exercise. During the static squat, the subjects held the same knee angle and the muscles were continuously twitched. On the other hand, during the dynamic squat exercise, the contraction is reduced in the higher angle phases.

CONCLUSIONS

For an exercise duration ? 60 sec, the static squat with WBV produced the higher neuromuscular and cardiorespiratory system activation. Otherwise, if the single bout duration is ? 60 sec, then, the WBV dynamic squat produced greater cardiorespiratory system activation while higher neuromuscular activation was still obtained with the static one. One limitation of our study is that only one muscle was investigated and, therefore, more research is required to investigate the behavior of other muscles. In addition, our research considered single bout exercises while a study performed during a long term period on groups of subjects that execute different kind of exercises would be helpful to understand better the causes responsible for the muscular response during WBV treatments.

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