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Human Response to Single and Combined Sinusoidal Vertical Vibration – Revisited

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ABSTRACT
In a 1977 study, task performance was shown to decline with exposure to combined vertical vibration, as opposed to single sinusoidal vibration. In the current study, electromyography was used to capture muscle activity of the back during single and combined whole-body vertical vibration to explore this phenomenon. Fourteen, right-handed males were exposed to four vertical vibration conditions (no vibration, 2.5 Hz, 5.0 Hz, and vibration combining 2.5 Hz with 5.0 Hz) while sitting upright. Subjects performed a four-limb task during testing. The participants were able to respond cyclically to the 2.5 Hz and 5 Hz vibration conditions when encountered independently, but only responded to the 2.5 Hz component of the combined vibration condition. Responding only at 2.5 Hz to a combined signal would allow the energy at 5.0 Hz to be dissipated elsewhere in the body, possibly explaining the performance decrement noted previously. This study has revealed a significant musculoskeletal control system limitation.

Keywords: Whole-body vibration, low back pain, performance, electromyography, complex vibration

1. INTRODUCTION

In the United States alone, there are some 3.5 million workers exposed to whole body vibration [1]. With regard to that exposure, low back pain (LBP) has a significant presence in the United States. LBP is also an expensive issue for the occupational arena, with low back workers' compensation costs approaching 11 billion dollars annually [2]. It has been shown that exposure to whole body vibration (WBV) is a significant risk factor for development of spinal disorders and low back pain in various occupations: helicopter pilots [3], tractor drivers [4-6], and construction equipment operators [7,8].

Whole body vibration in the occupational arena consists of a spectrum of vibration frequencies. Very few studies have been performed that examine how a carefully constructed spectrum affects the human body [9,10]. In a study performed by Cohen et al. in 1977, right-handed male participants were exposed to a control non-vibration condition and 3 different sinusoidal vertical vibration conditions: 2.5 Hz, 5 Hz, and a combination of 2.5 and 5 Hz [9]. The acceleration for all vibration conditions was 0.69 m/s^2 rms. These conditions were selected because 5 Hz is approximately the vertical natural frequency of the seated human, during which the phenomena of resonance may be produced [11], and 2.5 Hz is below the resonance band.

In Cohen et al.'s study, participants were asked to complete performance tasks using all four limbs while exposed to the vibration conditions. It was shown that operator performance was degraded the most during exposure to the combination of 2.5 and 5 Hz [9]. Although Cohen et al.'s study provides insight into the human performance response to complex vibration, it did not provide any physiological or biomechanical measurements.

With the advent of modern electromyography (EMG) instrumentation, the current study attempts to duplicate and revisit Cohen et al.'s 1977 study with the additional collection of EMG data to capture low back muscle activity. This is important because it may be able to explain the substantial decrease in performance that was encountered during exposure to the mixed signal.

It is hypothesized that the combination of the 2.5 Hz and 5 Hz frequencies of vertical vibration is mechanically aggravating to the body because it results in a vertical vibration that fluctuates between a high amplitude, low frequency acceleration and a low amplitude, high frequency acceleration (see Figure 1) within the seated human's range of fatigue, decreased proficiency sensitivity [12]. In the current study, the four different vertical vibration conditions (single 2.5 Hz, single 5 Hz, combined 2.5 and 5 Hz, and a non-vibration control) were applied to seated subjects. Trunk responses were monitored through the use and analysis of surface electromyography (EMG) of the left and right erector spinae muscles. These muscle groups were chosen because it has been shown that the erector spinae muscles are primarily responsible for support during forward flexed tasks [13].

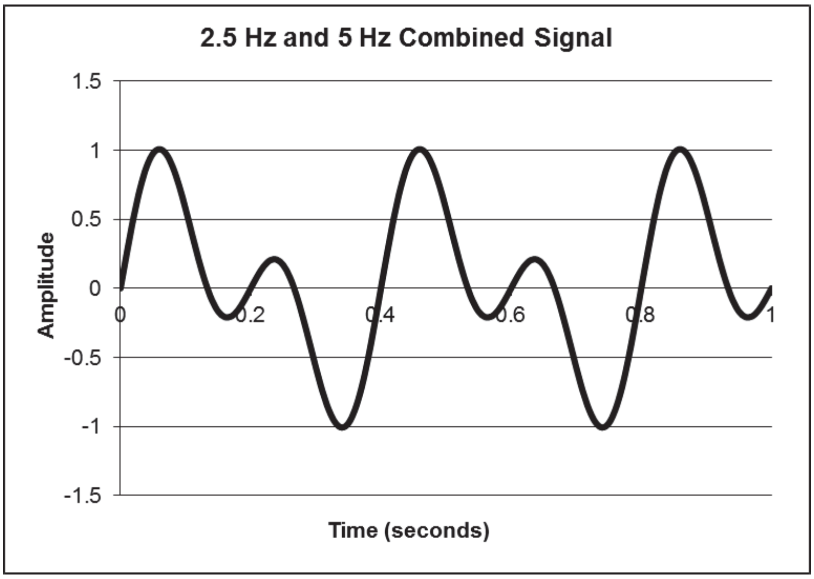


Figure 1. Idealized representation of the combined vertical vibration signal.

2. SUBJECTS AND METHODS

Fourteen right-handed males volunteered to participate in the current study. Participants ranged in age from 19 to 55, with an average age of 26 years (SD = 12, median = 21) average weight of 78.9 kg (SD = 9.88) and average height of 1.79 m (SD= 0.07). Exclusion criterion for this study prevented individuals reporting any history of back problems from participating. All participants were provided with the consent form (University of Iowa Institutional Review Board ID# 20071083), which was signed after it had been discussed and all questions had been answered. The participants were equipped with an emergency stop switch to stop their vibration exposure at any time.

As the purpose of this study was to characterize the trunk response to the specified vibration conditions, surface electromyography (EMG) was used to capture the muscle activity of the left and right lumbar erector spinae (LES and RES respectively) muscles. Two Ag-AgCl bipolar electrodes (Model D-100, Therapeutics Unlimited, Iowa City, IA, USA) with built in fixed pre-amplification of 35 were placed on the left and right lumbar erector spinae. Muscle electrical activity consists of the summation of asynchronously firing muscle motor units and in this study, exhibited frequency content only as high as 450 Hz. To eliminate low-frequency motion artifact, the effect of the EMG electrodes moving with the skin over the muscles, EMG signals were high-pass filtered at 70 Hz.

As in the prior study, each subject was exposed to four different vertical (z direction) vibration conditions while seated without the use of a seat belt. The four conditions were: (1) no vibration control, (2) 2.5 Hz vertical vibration (0.69 m/s^2 rms), (3) 5 Hz vertical vibration (0.69 m/s^2 rms), and (4) 2.5 Hz and 5 Hz combined vertical vibration (0.69 m/s^2 rms). The vibrations were produced with a six-degree-of-freedom Hydraudyne motion platform (Bosch-Rexroth, Netherlands) operating only in the vertical (z) direction in an effort to duplicate the 1977 study. Vertical acceleration was monitored at the seat-butt interface using a fixed Endevco seatpad accelerometer (San Juan Capistrano, CA) according to recommended practice SAE J1013 [14]. Data were sampled at 1 kHz, which exceeded the Nyquist criteria for sampling the EMG and acceleration signals. The participants were exposed to each vibration condition three times in random order, for a period of 30 seconds at a time. Two minutes of rest was provided between each vibration exposure.

The apparatus in which subjects were seated while being vibrated was constructed to resemble the four-limb coordination device used in the previous study to collect performance data [9]. The seat upon which the subjects sat was a bare metal tractor seat without a backrest, similar to the previous study [9]. Two joysticks and two foot pedals were constructed with 10 kΩ single-turn potentiometers and were secured to the same vibrating surface as the seat. The joysticks and foot pedals were attached to four digital multi-meters (two for the joysticks, and two for the foot pedals), which were capable of displaying resistance values (in kΩ). During vibration exposures, the participants were asked to complete a task that approximated the performance task that was conducted in the previous 1977 study. The performance data were not collected, as the emphasis in this study was on the addition of EMG activity to a well-established previous study.

As the current study was a replication of the Cohen, Wasserman, Hornung 1977 study, it was important that the participants assume the same posture during the testing as those used in that previous study. The upper arm was in-line with the spine (vertical) with the elbow bent to 90 degrees, so that the lower arm was perpendicular to the upper arm (Figure 2). One of us (Donald Wasserman) was involved in the previous study, and verified this posture. Participants were verbally reminded before each vibration exposure to maintain a straight back, or to "sit up straight." The joysticks were adjusted to a height to allow for the arm position described above, and the foot pedals were adjusted to meet the subjects' leg length.

The methodology developed in Seroussi, Wilder, and Pope's 1989 study was used in the EMG signal processing [15]. The EMG data were analyzed by first considering the LES and RES signals separately. For signal stability reasons, only the data collected between 10-25 seconds of the 30-second vibration exposure were analyzed. The EMG data were rectified, and then smoothed using a moving window average [16]. The same window used for the 2.5 Hz data was used for the combination vibration condition and the control conditions. From direct observation, it was determined that no information was lost by using the 2.5 Hz moving window average rather than a 5 Hz window. The smoothed EMG data were then ensemble-averaged into two cycles of the given vibration. Frequency analysis of LES and RES EMG data was performed as in the Seroussi et al paper [15]. The LES and RES muscles were assumed to be equal contributors of stabilizing forces.

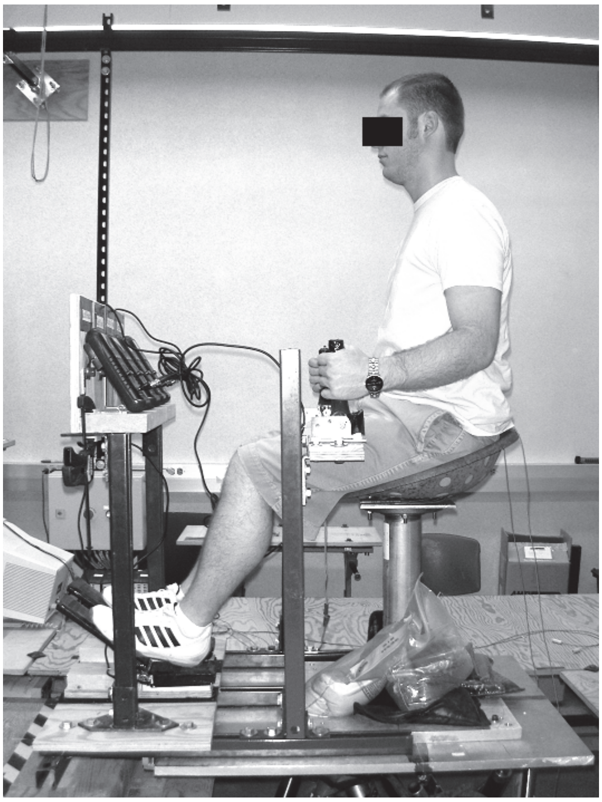


Figure 2. Participant posture during vibration exposure

3. RESULTS

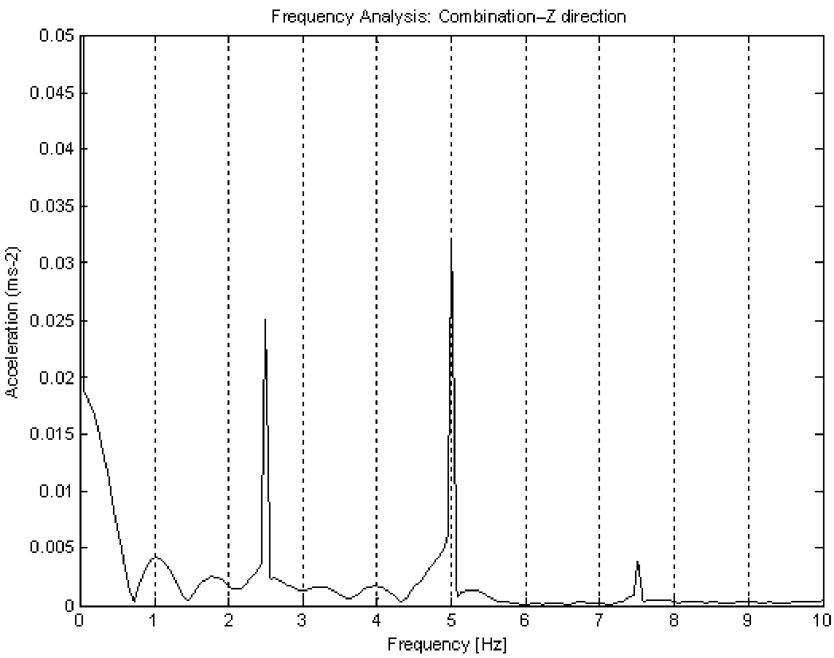
Frequency analysis was completed on the rectified and smoothed EMG signal from all participants' trials in each vibration condition. Not all participants responded cyclically to the vibration conditions (Table I).

Table I

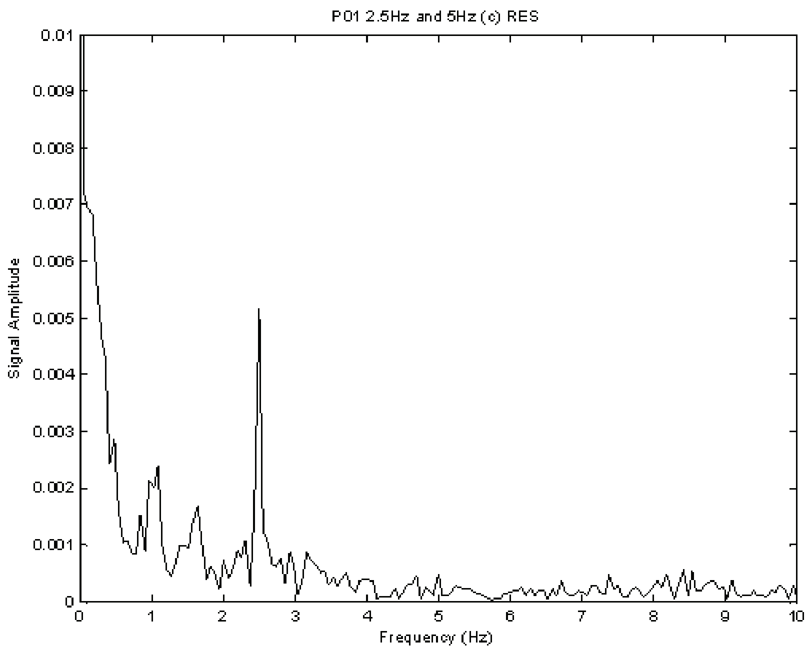
Frequency responses and number of participants, out of 14, who responded cyclically to each vibration condition.

Response	Vertical Vibration Condition					
	2.5 Hz		5 Hz		2.5 Hz and 5 Hz	
Erector Spinae	Left	Right	Left	Right	Left	Right
Frequency of Response	2.5 Hz	2.5 Hz	5 Hz	5 Hz	2.5 Hz	2.5 Hz
Number of Participants who Responded Cyclically	6	2	8	3	5	3

The participants who did demonstrate a cyclic response during the 5 Hz vibration exposure, indeed evoked erector spinae responses at the 5 Hz frequency. A similar trend was noticed for the 2.5 Hz vibration condition, with EMG signal amplitude being considerable at 2.5 Hz. Unexpectedly, during the combined vibration condition, when the participants did respond, they responded *only* to the 2.5 Hz component and *not* to the 5 Hz component of the signal (Figure 3).



(a)



(b)

Figure 3. (a) Frequency analysis of the combined vertical vibration input signal (b). Frequency analysis of right Erector Spinae muscle response to the combined vertical vibration condition

4. DISCUSSION

Some participants demonstrated very little response to the vibration conditions. The response, or lack of response, may be related to the posture in which the participants were seated during vibration exposure. The participants who sat erect, in-line and balanced with the vertical vibration vector were in a configuration that required little or no muscle activity from the erector spinae to maintain an upright posture. The reaction or lack of reaction may also be linked to the physiology of the muscluloskeletal control system, in that the subjects were unable to respond to the vibration conditions [11]. It has already been shown that the posture being maintained during vibration has a significant effect on the response of the erector spinae [17]. Further investigation of the participant posture during vibration exposure may reveal that the cyclic responses were obtained only when a slight forward flexed posture of the torso was assumed.

For those participants in the current study who did respond, the EMG frequency profile peaked at 2.5 Hz in the 2.5 Hz vibration condition, at 5 Hz in the 5 Hz vibration condition, and at *only* 2.5 Hz in the combined frequency vibration condition.

The present study has key implications. It has shown that the participants' erector spinae muscles were able to respond to the single vibration frequencies of 2.5 Hz and 5 Hz when exposed independently. When these vibrations were combined, the subjects' erector spinae muscles were consistently unable to respond to both frequencies simultaneously. The frequency analysis of the EMG responses showed that the participants who reacted cyclically to the combined frequency, responded *only* at 2.5 Hz.

This result is important, as one would expect to observe an EMG response that followed the input signal [15,18]. The new contribution of this work was to observe the muscle EMG response to a signal that combined both 2.5 Hz and 5 Hz. In the real world, one rarely experiences single sinusoidal vibration. Combining two sinusoids takes a very small step into the real world of complex vibration. If this were a linear system, one would expect to see valid superposition. This was not observed. It raises the question as to where in the body the energy from the 5 Hz signal is being dissipated. Ignoring the units and types of the respective signals, when the response signal (EMG activity) is subtracted from the combined vibration input signal (acceleration), the 5 Hz input component remains. The participants were only responding to the 2.5 Hz component of the signal, implying that the energy generated from the 5 Hz component was affecting some other area or system of the body. It has been well-established that the seated human is mechanically and psycho-physically sensitive to exposure to a 5 Hz vertical vibration [12]. This study has revealed a significant musculoskeletal control system limitation.

Cohen, Wasserman and Hornung's 1977 study demonstrated that exposure to the combination of 2.5 Hz and 5 Hz vibration resulted in increased fatigue and decreased performance. This study's finding of the lack of muscle response to the 5 Hz component of the combined input signal is likely correlated with the fatigue and performance degradation that was discovered then.

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