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Combined Effects of Noise and Hand-transmitted Vibration on Workers' Muscle and Mental Fatigues in a Simulated Construction Operation

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Abstract

Background: *The frequent use of hand-held vibrating tools by construction workers exposes them to hand-transmitted vibration (HTV) and noise. This study investigated the effect of combined exposure to HTV and noise on workers' fatigues under simulated work with a typical building destruction tool.* **Methods:** *The repeated measures study was conducted on 40 construction workers exposed to HTV (5 m/s2 rms with frequencies of 31.5, 63, and 125 Hz), HTV (10 m/s2 rms- 31.5 Hz), noise (90 dBA), and concurrent exposure (noise (90 dBA) + HTV (10 m/s2 rms- 31.5 Hz)) with the typical vibrating hand-held tool for 30 minutes. Electromyography signals determined each worker's fatigue level in the Flexor digitorum superficialis (FDS) muscle in two pre- and post-exposure periods. The subjects also filled out the visual analog scale to evaluate mental fatigue severity subjectively.* **Results:** *The mean difference of muscle fatigue parameters was significant in all scenarios except for the two scenarios of alone exposure to HTV (5 m/s2 -125 Hz) and noise exposure (p-value < 0.05). The mean difference of mental fatigue in all scenarios except for the two scenarios of exposure to HTV (5 m/s2 -125 Hz) and exposure to HTV (5 m/s2 -63 Hz) was significant (p-value < 0.05). The most differences in muscle fatigue parameters (Amplitude = 8.16±5.63, Mean frequency=-4.69±3.78) and mental fatigue (4.97±2.38) were observed in the simultaneous exposure to noise and HTV.* **Conclusion:** *Noise exposure alone cannot produce remarkable effects on muscle fatigue but can aggravate the effects of vibrations as a consequence of synergistic interaction. However, the role of noise on perceived mental fatigue was more dominant than the HTV. These findings should be considered to adapt the existing exposure limits to actual work conditions.*

1. Introduction

Electric or pneumatic vibrating hand-held tools are employed in many professions, such as repair operations, industrial production, and construction. Working in such vibration conditions for a long time may increase the hand-arm vibration syndrome (HAVS) risk. The prevalence of HAVS varies in

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different countries; for example, 72,000 to 140,000 workers in Canada, 20,000 workers in the Netherlands, approximately 2,5 million workers in the United States, and 110,000 workers in Hong Kong are estimated to be exposed to hand-transmitted vibration (HTV) [1-3].

The construction industry is a leading and central pillar of the economy, which is expanding rapidly in many developed countries and cities. In this context, it is necessary to use construction machinery and vibrating tools such as jackhammers, grinding stones, screwdrivers, concrete vibrators, drills, and various cutting tools for different construction activities. When working with this type of vibrating tool, different acceleration levels of mechanical vibration are produced, and in this way, construction workers are exposed to HTV. As a result, it will be crucial to investigate the effects of HTV on construction workers; it is considered a severe occupational hazard for those who work with these vibrating tools. According to the nature of their job activities, construction workers need high physical and mental capacities to perform their tasks and must have good health and workability [1, 4, 5]. Besides vibration, exposure to noise pollution is one of the most critical factors affecting construction workers' health and abilities. Vibration sometimes intensifies noise and can even be the cause or source of noise production, as many vibrating tools are noisy. Co-exposure to vibration and noise may also occur during construction operations [4, 6].

HTV is a type of local vibration that involves the upper limbs; it causes vascular, sensory-neural, and musculoskeletal disorders collectively called hand-arm vibration syndrome [3, 7]. The neuromuscular responses, manifested in fatigue and muscle tension of upper limbs, are very significant in terms of the power to do the work. Widia et al. [8], Dewangan et al. [9], and Lai et al. [1] showed that vibration is transmitted from the handles to the hands, arms, and shoulders, causing the operator's discomfort and fatigue. In addition, due to the concurrent exposure of noise and vibration when working with these vibrating tools, noise can also create muscle tension. However, the studies showed that this issue has rarely been addressed objectively, and there are limited and contradictory studies in this field [10-12].

In addition to vibration intensity, direction, exposure time, and frequency, coupling forces and hand-arm posture can be identified as essential factors affecting muscle fatigue. Some studies investigated the effects of biodynamic factors such as coupling forces and hand-arm posture on the level of vibration transmission to the hands and its consequences. These factors are identified in Annex D of ISO 5349-1. Furthermore, the frequency content of the vibration influences the health risk caused by vibration, so some hand-held vibrating tools can generate significant vibrations at low frequencies and cause them to be transmitted to different areas of the body in the upper limbs, including arms, shoulders, back, neck, and even head [13-15]. As a result, the HTV frequency and vibration intensity can affect muscle responses and mental fatigue.

Studies have recommended that these biodynamic factors be considered when assessing workers' potential risk of disorders. However, the role of noise as one of the main physical factors in creating effects caused by simultaneous exposure to vibration has still not been clarified. It is observed that noise and HTV in many jobs with vibrating hand-held tools occur simultaneously and inseparably. Therefore, the exposure risk assessment should not be considered one-dimensionally and separately. Few studies investigated the effects of concurrent exposure to noise and HTV on different aspects of fatigue. As a result, the present study investigates the effect of HTV intensity and frequency on fatigue. It also deals with the effect of concurrent exposure to noise and HTV on construction industry workers' muscle and mental fatigue.

2. Methods

2.1 Subjects

The repeated measures study was experimentally conducted on 40 volunteer construction workers who had experience working with manual vibrating demolition tools. The inclusion criteria were having at least one year of experience working with vibrating tools; having the age range of 25-35 years; not having discomfort and MSDs in the upper limbs (neck, shoulder, arm, elbow, wrist, etc.); not suffering from cardiovascular diseases, not suffering from respiratory and neurological disorders; not suffering from immunodeficiency diseases; having good general health (investigated through the General Health Questionnaire – 28 (GHQ-28) [16, 17] with a total score of less than 23; having no noise sensitivity (checked through the Weinstein Noise Sensitivity Scale (WNSS) [18] with a score of less than 75; having no record of drug abuse, smoking, and alcohol, not drinking liquids containing caffeine on the test days; having no record of taking cardiac drugs, anti-depressants, sedatives, and muscle drugs at least in the last month; having normal hearing and vision; and having no sleep disorders. The research team examined these inclusion criteria through self-reports and standard questionnaires. An invited specialist measured the worker's hearing and vision abilities. This study protocol has been confirmed by the Ethics Committee of Hamadan University of Medical Sciences (ethics code: IR.UMSHA.REC.1400.657), and the workers who met the inclusion criteria signed informed consent before participating in the study.

2.2 Exposure Condition Simulations

All the experiments were carried out in the environmental physiology laboratory of the Occupational Health Department of Hamadan University of Medical Sciences. Illuminance measurement was done with the Hagner Digital Luxmeter, model EC1, based on measuring the work surface's general height and 6 IES patterns and showed the illumination intensity within the permissible limits of the occupational exposure standard (300 lux). In addition, the laboratory air temperature and humidity were measured on different days using Casella Microtherm Heat Stress WBGT: the dry air temperature was controlled and fixed in the range of 22.1-23°C with an average of 22.5 °C, and relative humidity in the range of 50-53.7% with an average of 51.4%.

This experimental study was conducted on construction workers who were exposed to HTV (5 m/s2 rms -125 HZ), HTV (5 m/s2 rms- 63 HZ), HTV(5 m/s2 rms -31.5 HZ), HTV(10 m/s2 rms -31.5 HZ), noise (90 dBA) and concurrent exposure [HTV(10 m/s2 rms -31.5 HZ) + noise 90 dBA] to them for 30 minutes for six sessions under simulated work with building vibrating demolition tools. It should be noted that the exposures consisted of 6 exposure periods of 5 minutes. A one-minute interval was considered between each exposure period (5 rest periods).

Based on the pre-test field measurements among real construction sites, the vibration and noise values were selected to correspond to typical electric demolition jackhammers' noise and vibration content. The field data showed that during the destruction of the building floor employing the current medium-weighted jackhammers, most workers were exposed to the vibration and noise of 10 m/s2 and 90 dBA. Therefore, three considered scenarios as HTV (10 m/s2 rms -31.5 HZ), noise (90 dBA), and concurrent exposure (HTV(10 m/s2 rms -31.5 HZ) + noise 90 dBA) were selected based on field measurements. It should be noted that the ACGIH-TLVs were also considered to design other exposure scenarios [19]. An electrodynamic shaker induced the HTV with two handles and an amplifier connected to Lab VIEW (2018) with the ability to adjust the different intensities and frequencies of the vibration in this system. The capacity of this electrodynamic shaker was 500 newtons. It could produce different vibration accelerations in the 1-500 Hz frequency range. Furthermore, it could be adjusted and rotated at different angles to simulate the real workstation accurately. This study simulated working with jackhammers to demolish the building floor as an everyday activity, and a dynamometer measured and displayed the push force with an accuracy of 0.2 kg. The amount of vibration reached by the participants' hands was measured by SVANTEK hand-arm accelerometer connected to SV 106 6-channel vibration meters according to ISO 5349 standard [20] in three x, y, and z axes. As mentioned, the participants were exposed to 31.5, 63, and 125 Hz vibrations with a weighted equivalent acceleration of 5 m/s2 rms and 31.5 Hz vibration with a weighted equivalent acceleration of 10 m/s2 rms for 30 minutes along the arms of both hands (predominantly on the z-axis). The vibration spectrums at two acceleration levels (both unweighted and weighted) according to the international standard

Table 1. The vibration spectrums at two acceleration levels for simulating the exposure scenarios.

Exposure scenario	Acceleration (m/s^2, rms)	Frequency (Hz)									
		4	8	16	31.5	63	125	250	500	1000	Total
HTV (5 m/s^2 rms -125 Hz)	*ahi(Z)*	0.016	0.018	0.03	0.092	0.203	32.23	18	0.628	0.206	36.92
	ahw(Z)	0.006	0.015	0.026	0.047	0.051	4.093	1.141	0.019	0.002	4.25
	ahi(y)	0.017	0.019	0.025	0.05	0.059	13.60	4.35	0.197	0.187	14.29
	ahw(y)	0.006	0.016	0.022	0.025	0.015	1.727	0.275	0.006	0.002	1.75
	ahi(x)	0.022	0.029	0.043	0.063	0.153	15.29	5.16	0.343	0.324	16.14
	ahw(x)	0.008	0.025	0.038	0.032	0.039	1.941	0.327	0.01	0.004	1.97
HTV (5 m/s^2 rms -63 Hz)	*ahi(Z)*	0.022	0.025	0.027	0.033	16.65	4.05	3.47	0.279	0.179	17.49
	ahw(Z)	0.008	0.021	0.024	0.017	4.263	0.514	0.219	0.008	0.002	4.3
	ahi(y)	0.021	0.023	0.025	0.04	7.816	2.24	1.89	0.217	0.193	8.2
	ahw(y)	0.007	0.02	0.022	0.02	2.001	0.284	0.119	0.068	0.026	1.45
	ahi(x)	0.02	0.03	0.041	0.06	8.034	3.15	2.04	0.257	0.323	8.88
	ahw(x)	0.007	0.026	0.036	0.031	2.056	0.4	0.129	0.008	0.004	2.1
HTV (5 m/s^2 rms -31.5 Hz)	*ahi(Z)*	0.199	0.232	0.025	8.307	2.07	0.523	0.667	0.151	0.191	8.62
	ahw(Z)	0.074	0.202	0.022	4.311	0.529	0.066	0.042	0.004	0.002	4.35
	ahi(y)	0.014	0.017	0.022	3.7	0.589	0.107	0.131	0.161	0.19	3.76
	ahw(y)	0.005	0.014	0.019	1.92	0.15	0.013	0.008	0.005	0.002	1.44
	ahi(x)	0.021	0.032	0.042	3.866	0.399	0.221	0.187	0.233	0.323	3.92
	ahw(x)	0.007	0.027	0.037	2.006	0.102	0.028	0.011	0.007	0.004	2.01
HTV (10m/s^2 rms -31.5 Hz)	*ahi(Z)*	0.037	0.043	0.047	15.01	4.02	0.986	1.14	0.284	0.358	15.62
	ahw(Z)	0.013	0.037	0.042	7.79	1.029	0.125	0.072	0.008	0.004	7.86
	ahi(y)	0.026	0.034	0.038	7.07	3.02	0.421	0.516	0.299	0.353	7.73
	ahw(y)	0.009	0.029	0.034	3.671	0.773	0.053	0.032	0.009	0.004	3.76
	ahi(x)	0.041	0.049	0.078	9.408	2.3	0.43	0.366	0.454	0.629	9.74
	ahw(x)	0.015	0.034	0.062	4.883	0.593	0.054	0.023	0.014	0.008	4.92

a_{hi}: Unweighted acceleration (m/s^2, rms), a_{hw}: Frequency-weighted acceleration (m/s^2, rms).

ISO 5349 [20] used to simulate the exposure scenarios are displayed in Table 1.

For noise exposure scenario, the participants were exposed to the recorded noise of a typical electric demolition jackhammer with equivalent noise level of 90 dBA. The noise was played by an OS003-BSWA spherical speaker and a BSWA audio amplifier SWA-100 connected to a laptop and was located at a distance of one meter from the participants. Their noise exposure was monitored by SVANTEK 971 Sound Level Meter and by installing SVANTEK 104 dosimeter on the participants' collars.

2.3 Experimental Procedure

The study used a within-subjects design, where all subjects were considered as their controls. A repeated-measures design was conducted, and the participants randomly received HTV exposure, noise exposure, and concurrent exposure for 30 minutes in six days with a minimum interval of 24 hours. The participants' postures in the case of different exposure scenarios are shown in Figure 1. The device's height was adjusted according to the participants' heights using wooden and concrete cubes of a specific size. It should be noted that the subjects' natural body and

Figure 1. Experimental setup for simulating exposure to HTV and/or noise.

hand postures as the fixed main biodynamic factor corresponded to the observed real workstation during the destruction of building floors in all exposure scenarios, as shown in Figure 1.

50 N push forces are average hand forces applied in many tool operations. Therefore, the current study also controlled the push forces at 50±8 N.

The participants held the vibrating tool handle with a standard grip (20% of their maximum voluntary contraction power), similar to the recommendation of some references such as ISO 10819 [21-24]. The push forces were monitored and displayed on two virtual dial gauges on two digital monitors in front of the subject, as shown in Figure 1.

During exposure to HTV, the participants wore hearing protection devices (ear muffs). Measurement of noise by the SVANTEK 102 noise dosimeter showed that the background noise during exposure to HTV without hearing protection devices was 64 dBA and reduced up to 52 dBA using the approved ear muffs. Before starting each test, the participants rested for 15 minutes in the calm conditions of the test chamber. Generally speaking, the participants' exposure includes six 5-minute consecutive episodes with 1-minute silence (rest) periods between scenarios. Furthermore, the results can be different on different days and hours. Therefore, participants were compared and checked with their baselines.

For each scenario, electromyographic activity (EMG) of the Flexor digitorum superficialis (FDS) muscle and the perceived mental fatigues of subjects were measured in two periods, pre- and post-exposure.

2.4 Subjective Measurement of Mental and Muscle Fatigues

The visual analog scale to evaluate fatigue severity (VAS-F) [with 10 points (0=no fatigue and 10 = maximum fatigue)] was employed to measure mental fatigue subjectively. Subjects were asked to score their level of mental fatigue from 0 to 10, according to Figure 2 [25, 26].

The current study also used a body map to select muscles to check muscle fatigue. Before starting the laboratory phase of the study in the investigated work environment, 60 workers were asked, when working with manual vibrating demolition tools, which area of the upper limbs indicated in Figure 3 do they feel the most fatigue or pain.

In this way, the subjective evaluation of muscle fatigue was done, and the greatest frequency of fatigue or pain reported among these 60 workers was position number 5, with a frequency of 25 workers, which is related to forearm/elbow muscles. Besides, studies have shown that the flexor digitorum superficialis (FDS) muscle, located in the anterior part of the forearm, plays an essential role in maintaining the position of the forearm, holding and carrying objects, and gripping and bending the fingers. Therefore, the proper functioning of this muscle in working with hand tools seems necessary to do the job correctly and prevent safety-related consequences [10, 25, 26]. Hence, using the EMG method, the FDS muscle was chosen to investigate objective fatigue.

2.5 EMG Method

Electromyography (EMG) reveals the electrical potential muscle cells produce when these cells are electrically or neurally activated. In the current study, using a Nexus-4 device with a sampling rate of 2048/sec and a bandwidth of 10-500Hz, the FDS muscle signal was recorded for 2 minutes in pre-and

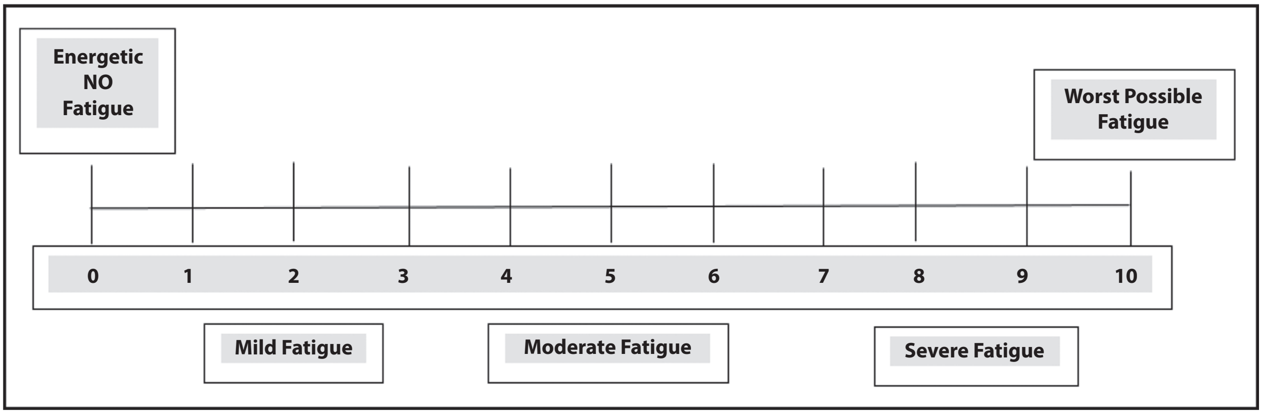

Figure 2. The visual analogue scale to evaluate fatigue severity (VAS-F).

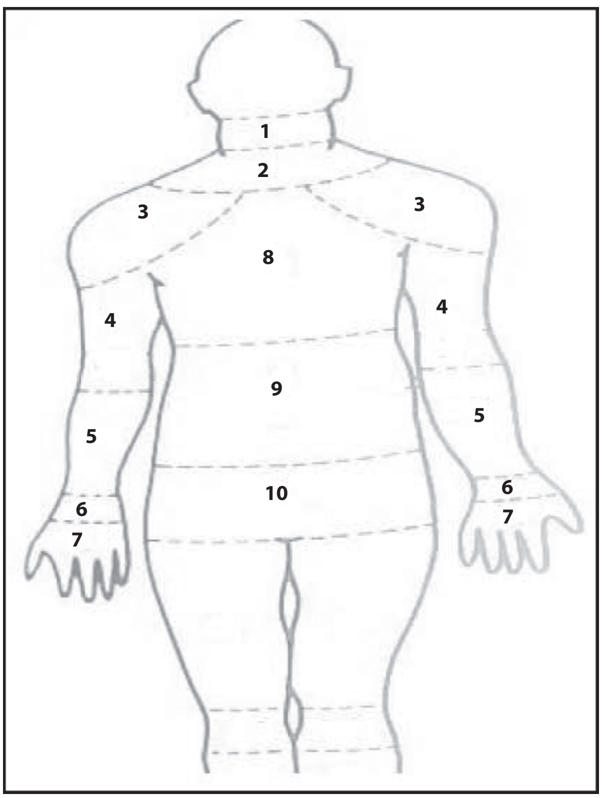

Figure 3. Body map for subjective measurement of muscle fatigue.

post-exposure periods while the subject was sitting on a chair with an average body position (straight back, the appropriate height of the chair with 90-degree knee angle and soles of feet on the floor).

Electrode placement and noise control were done based on the guidelines of the Surface EMG for Non-Invasive assessment of Muscles (SENI-ANM) convention. To reduce skin resistance, the sites to place the electrodes were cleaned by removing excess hair and rubbing it with alcohol. Next, the electrodes were placed parallel to the direction of the muscle fibers and at a distance of 2 cm (center to center) from each other on the protrusion of the muscle center and in the middle distance of the medial epicondyle (half the distance between the medial epicondyle of the humerus and the ulnar styloid process) [10, 27]. Figure 4 displays the sites of the electrodes on the muscle and the reference electrode. The recorded signals were checked and analyzed by BioTrace+ Software. Finally, the Joint Analysis of Spectrum and Amplitude (JASA) method was used to identify muscle fatigue. This method checks the amplitude of a signal and spectrum changes and analyzes simultaneously. In the current study, Root Mean Square (RMS) considered the amplitude modulation index and mean frequency to measure the EMG signal spectrum. Accordingly, the increase in the amplitude simultaneous to the decrease in the frequency spectrum is a sign of fatigue in the desired muscle [28].

2.6 Statistical Analysis

IBM SPSS Statistics 25 was employed for data analysis. Concerning the normal distribution of the data, the paired sample t-test was used to compare the mean scores in the pre-and post-exposure periods. Repeated-measures ANOVA was used to compare

Figure 4. Sites of electrode placement on FDS muscle and reference electrode.

the mean difference in different exposure scenarios. Pearson's correlation was used to determine the association between EMG parameters and mental fatigue. A p-value less than 0.05 was statistically established as the limit for statistical significance.

3. Results

The mean and standard deviation of age, work experience, height, and weight of the workers who participated in the current study were 30.52±3.53(year), 3.75±1.82(year), 1.77±0.06(m), 72.37±7.28(kg), respectively. In addition, the general health score and noise sensitivity score of the subjects were also 16.22±4.05 and 53.55±14.65, respectively.

The mean difference and standard deviation of EMG parameters in the pre-and post-exposure periods in all exposure scenarios are shown in Table 2. A relative increase in amplitude and a relative decrease in the frequency of the post-exposure were observed in the recorded EMG waves for all scenarios except the HTV (5 m/s2 rms -125 Hz). A comparison of the difference of means for pre- and post-exposure periods did not show a significant difference for EMG parameters in two scenarios of exposure to noise exposure scenario and HTV (5 m/s2 rms -125 Hz) scenario. However, these changes were significant in the other four scenarios (p-value < 0.05). The most changes in pre-and post-exposure periods were also observed for the concurrent exposure to HTV and noise scenario.

The changes in the mean and standard deviation of mental fatigue in the pre-and post-exposure periods in the six scenarios are shown in Table 3.

The paired t-test results showed that the mean changes for the HTV (5 m/s^2 rms -125 Hz) and (5 m/s^2 rms -63 Hz) scenarios are not significant in the before- and after-exposure periods while it is significant in the other four scenarios (p-value <0.05). The most of the mean difference was also observed in the concurrent exposure to HTV and noise scenario.

This study employed repeated measures ANOVA to investigate the mean difference between EMG parameters and mental fatigue in different exposure scenarios. The results showed that the mean difference between EMG parameters and mental fatigue in different exposure scenarios had a significant difference (p-value<0.05).

The results of the LSD follow-up test and the effect size of each exposure scenario on mental fatigue scores and EMG parameters are shown in Table 4. The results showed that concurrent exposure to HTV and noise had the most significant effect on changes in the amplitude, frequency, and mental fatigue of the studied subjects, with an effect size of 0.683, 0.612 and 0.818, respectively.

As shown in Table 4, based on the estimated effect sizes, the effect of exposure to HTV on muscle fatigue was stronger than noise. However, in combined exposure, noise has increased the dominant effect of HTV on muscle fatigue. The effect of noise on mental fatigue was greater than that of HTV. However, in combined exposure, vibration has increased the dominant effect of noise on mental fatigue. It is observed that the low-frequency HTV (5 m/s^2 rms -31.5 Hz) showed a more significant effect on muscle and mental fatigue than

Table 2. The mean difference of EMG waves amplitude and frequency in all exposure scenarios.

Exposure scenario	Variables	Mean difference ± SD	P-Value
HTV (5 m/s^2 rms -125 Hz)	Amplitude (µv rms)	0.3±2.69	0.478
	Mean frequency (Hz)	0.12±2.67	0.761
HTV (5 m/s^2 rms -63 Hz)	Amplitude (µv rms)	1.28±3.53	0.027
	Mean frequency (Hz)	-0.89±2.79	0.049
HTV (5 m/s^2 rms -31.5 Hz)	Amplitude (µv rms)	2.17±3.87	0.001
	Mean frequency (Hz)	-1.78±3.02	0.001
HTV (10 m/s^2 rms -31.5 Hz)	Amplitude (µv rms)	5.43±4.83	<0.001
	Mean frequency (Hz)	-2.62±3.56	<0.001
Noise (90dBA)	Amplitude (µv rms)	0.489±2.23	0.173
	Mean frequency (Hz)	-0.56±1.68	0.039
Noise (90dBA) + HTV (10 m/s^2 rms -31.5 Hz)	Amplitude (µv rms)	8.16±5.63	<0.001
	Mean frequency (Hz)	-4.69±3.78	<0.001

Table 3. The mean and standard deviation of mental fatigue score for pre-and post-exposure.

	Mean scores±SD			
Exposure scenarios	**Pre-exposure**	**Post-exposure**	**Mean difference ±SD**	**P-Value**
HTV (5 m/s^2 rms -125 Hz)	1.42±0.95	1.50±1.13	0.08±0.85	0.584
HTV (5 m/s^2 rms-63 Hz)	1.72±0.98	2.07±1.38	0.35±1.12	0.056
HTV (5 m/s^2 rms-31.5 Hz)	1.45±0.95	2.67±1.45	1.22±1.34	<0.001
HTV (10 m/s^2 rms-31.5 Hz)	1.25±0.83	3.27±1.35	2.02±1.44	<0.001
Noise (90dBA)	1.4±1.05	4.72±1.53	3.32±1.80	<0.001
Noise (90dBA) + HTV (10 m/s^2 rms-31.5 Hz)	1.30±1.34	6.27±1.92	4.97±2.38	<0.001

high-frequency HTV (5 m/s^2 rms -63 Hz and 125 Hz). This study also showed that for four HTV (5 m/s^2 rms -63 Hz), HTV (5 m/s^2 rms - 31.5 Hz), HTV (10 m/s^2 rms -31.5 Hz), and concurrent exposure scenarios, a significant correlation was observed between subjective and objective fatigue responses (p-value<0.05). The results of the Pearson correlation between EMG records and mental fatigue are displayed in Table 5.

4. Discussion

Given the nonlinear nature of the hand–arm vibration responses, this study is thus aimed to investigate the effects of the noise under varying levels of vibration excitation and spectrums. Based on the findings, it can be said that HTV had a more significant effect on muscle, and noise exposure increased the dominant effect of HTV on muscle fatigue. Furthermore, by comparing the effect sizes observed for the changes of amplitude and mean frequency in three scenarios with the same acceleration of 5 m/s2 rms and different frequencies of 125 Hz, 63 Hz, and 31.5 Hz, it can be said that lower HTV frequencies had a greater effect size on muscle fatigue. Moreover, increasing the acceleration of HTV with the same frequency of 31.5 Hz from 5 m/s2 rms to 10 m/s2 rms significantly increased muscle fatigue (Table 4).

The results of muscle activation level changes in the present study are consistent with Widia et al., who showed that different HTV levels ranging from 10.24 m/s2 rms to 10.69 m/s2 rms (5 minutes and 15 minutes) could increase the range of electromyographic waves recorded from muscles and reduce its power spectrum (an EMG muscle fatigue

Table 4. The pairwise comparison and the effect size of EMG data and mental fatigue in all exposure conditions.

Variables	Exposure scenario	HTV (5 m/s^2 rms -125 Hz)	HTV (5 m/s^2 rms -63 Hz)	HTV (5 m/s^2 rms -31.5 Hz)	HTV (10 m/s^2 rms -31.5 Hz)	Noise (90dBA)	Noise (90dBA) + HTV (10 m/s^2 rms -31.5 Hz)	Effect Size
Amplitude (µv rms)	HTV (5 m/s^2 rms -125 Hz)	-	0.144	0.022	<0.001	0.762	<0.001	0.013
	HTV (5 m/s^2 rms -63 Hz)	0.144	-	0.112	<0.001	0.229	<0.001	0.119
	HTV (5 m/s^2 rms -31.5 Hz)	0.022	0.112	-	<0.001	0.021	<0.001	0.244
	HTV (10 m/s^2 rms -31.5 Hz)	<0.001	<0.001	<0.001	-	<0.001	0.007	0.564
	Noise (90dBA)	0.762	0.229	0.021	<0.001	-	<0.001	0.047
	Noise (90dBA) + HTV (10 m/s^2 rms -31.5 Hz)	<0.001	<0.001	<0.001	0.007	<0.001	-	0.683
Mean frequency (Hz)	HTV (5 m/s^2 rms -125 Hz)	-	0.085	0.004	<0.001	0.177	<0.001	0.02
	HTV (5 m/s^2 rms -63 Hz)	0.085	-	0.190	0.008	0.581	<0.001	0.196
	HTV (5 m/s^2 rms -31.5 Hz)	0.004	0.190	-	0.091	0.024	<0.001	0.262
	HTV (10 m/s^2 rms -31.5 Hz)	<0.01	0.008	0.091	-	0.03	0.01	0.358
	Noise (90dBA)	0.177	0.581	0.024	0.003	-	<0.001	0.104
	Noise (90dBA) + HTV (10 m/s^2 rms -31.5 Hz)	<0.001	<0.001	<0.001	0.001	<0.001	-	0.612
Mental fatigue	HTV (5 m/s^2 rms -125 Hz)	-	0.202	<0.001	<0.001	<0.001	<0.001	0.08
	HTV (5 m/s^2 rms -63 Hz)	0.202	-	0.001	<0.001	<0.001	<0.001	0.091
	HTV (5 m/s^2 rms -31.5 Hz)	<0.001	0.01	-	<0.001	<0.001	<0.001	0.458
	HTV (10 m/s^2 rms -31.5 Hz)	<0.001	<0.001	<0.001	-	<0.001	<0.001	0.669
	Noise (90dBA)	<0.001	<0.001	<0.001	<0.001	-	<0.001	0.777
	Noise (90dBA) + HTV (10 m/s^2 rms -31.5 Hz)	<0.001	<0.001	<0.001	<0.001	<0.001	-	0.818

Table 5. Correlation between the EMG parameters and mental fatigue in different exposure scenarios.

		Amplitude (μv rms)		Mean frequency (Hz)		Mental fatigue	
Exposure scenario	**Variables**	**Correlate**	**P-Value**	**Correlate**	**P-Value**	**Correlate**	**P-Value**
HTV (5 m/s² rms -125 Hz)	**Amplitude (μv rms)**	1	-	-0.140	0.389	0.117	0.473
	Mean frequency (Hz)	-0.14	0.389	1	-	-0.229	0.155
	Mental fatigue	0.117	0.473	-0.229	0.155	1	-
HTV (5 m/s² rms -63 Hz)	**Amplitude (μv rms)**	1	-	-0.393	0.012	0.338	0.033
	Mean frequency (Hz)	-0.393	0.012	1	-	-0.380	0.015
	Mental fatigue	0.338	0.033	-0.380	0.015	1	-
HTV (5 m/s² rms -31.5 Hz)	**Amplitude (μv rms)**	1	-	-0.419	0.007	0.397	0.011
	Mean frequency (Hz)	-0.419	0.007	1	-	-0.446	0.04
	Mental fatigue	0.397	0.011	-0.446	0.04	1	-
HTV (10 m/s² rms-31.5 Hz)	**Amplitude (μv rms)**	1	-	-0.619	<0.001	0.415	0.008
	Mean frequency (Hz)	-0.619	<0.001	1	-	-0.556	<0.001
	Mental fatigue	0.415	0.008	-0.556	<0.001	1	-
Noise (90dBA)	**Amplitude (μv rms)**	1	-	-0.252	0.116	0.153	0.346
	Mean frequency (Hz)	-0.252	0.116	1	-	-0.052	0.750
	Mental fatigue	0.153	0.346	-0.052	0.750	1	-
Noise (90dBA) + HTV (10 m/s² rms 31.5 Hz)	**Amplitude (μv rms)**	1	-	-0.684	<0.001	0.538	<0.001
	Mean frequency (Hz)	-0.684	<0.001	1	-	-0.594	<0.001
	Mental fatigue	0.538	<0.001	-0.594	<0.001	1	-

symptom) [8]. Among other studies with similar results to the present study, we can refer to Park et al. [29], and Bovenzi et al [30]. Park et al. indicated that the EMG signal output values decreased after exposure to HTV, indicating decreased muscle activation. Also, the mean frequency value change after exposure to HTV was significantly reduced. Bovenzi and colleagues showed that upper limb MSDs in HTV-exposed workers was greater than in the control group: as exposure to HTV increased, the incidence of elbow/forearm and wrist/hand skeletal disorders increased. Lu et al. (2019) depicted that the whole body's vertical vibration and the sitting position significantly affect muscle fatigue of the trunk muscles and discomfort, which is consistent with the results of the present study [31].

Kim et al. showed that noise of 90 dBA increased trunk muscle fatigue, and when playing soft music as a background, trunk muscle fatigue was the least [12]. As a result, noise affects muscle fatigue from a certain point onward, which is consistent with the results of the present study. Meanwhile, the results of the effect of noise on muscle activation have been reported differently. Bidel et al. showed that when exposed to three noise levels of 75 dBA, 85 dBA, and 95 dBA in different temperature conditions, the changes in the electrical activation of the FDS and the biceps muscle do not have a clear trend. In some scenarios, a rise in the noise level decreased muscle activation; in others, it increased the electrical activation of the muscle [10]. Kristiansen et al. indicated that noise of 65 dB for 35 minutes did not affect the level of electrical activation of the trapezius (i.e., when both the left and right muscles contract) [32]. On the other hand, Jancke et al. showed that a rise in the noise level increased the activation of facial muscles [11].

Exposure to HTV, especially at lower frequencies and greater intensities, seems to affect fatigue symptoms more than noise substantially. Therefore, it can be stated that exposure to HTV, in addition to the stress load on the hand, is also considered physical muscle activation and imposes a double load on the exposed workers. As a result, it causes more fatigue than exposure to noise alone. Also, if the vibration acceleration is low, considering that the muscle energy metabolism is predominantly aerobic in this condition, fatigue appears later. However, in exposure to vibration with greater accelerations, the oxygen required by the muscles becomes more than the oxygen available in the blood circulation. Accordingly, the accumulation of lactic acid and more muscle effort causes fatigue in the short run [33, 34].

The present study showed that noise caused a slight increase in amplitude and a slight decrease in frequency. Also, in concurrent exposure to noise and HTV, noise could significantly increase the effect of HTV on muscle tension. It may be because exposure to noise as a stimulus can change the electrical activation of the muscle by influencing and stimulating the activation of alpha and gamma motor neurons, which are responsible for innervating the muscle fibers and stimulating the vestibular system, which leads to the creation of acoustic motor reflexes [10].

The results of the present study related to mental fatigue showed that concurrent exposure to noise and HTV (10 m/s2 rms -31.5 Hz) had the most significant effect on the subjects' mental fatigue than the independent noise exposure scenario and other scenarios with the greatest mean difference (4.97±2.38) and effect size (ES=0.818). Also, according to the observed effect size for changes in mental fatigue in three scenarios of noise exposure, HTV exposure (10 m/s2 rms -31.5 Hz), and concurrent exposure, which were 0.777, 0.669, and 0.818, respectively, it can be said that noise had a greater effect than HTV. In addition, HTV increased the effect of noise on mental fatigue.

Jahcke et al. (2011 & 2013) showed that people exposed to high noise levels reported more mental fatigue than those exposed to low noise levels [35, 36]. Another study revealed that mental fatigue increased by about 40% in the noise-exposure group compared to the control group [37].

Jiao et al. showed that exposure to body vibration affects the level of fatigue perceived by people; they stated that different vibration frequencies cause different levels of mental stress and fatigue in people [38]. Ljungberg et al. examined the subjective experience of individuals with independent and concurrent exposure to body vibration and noise, and the subjects significantly rated the concurrent exposure mode as the most annoying and difficult period [39].

This study showed that exposure to occupational noise has a stronger and more dominant role in the incidence of perceived mental fatigue than HTV. The possible reasons for these results are that noise as a stress factor leads to changes in the body of the exposed person. As a result, in response to the noise-induced stress, the impulses from the greater cortex areas are transferred to the hypothalamus through the limbic system, which releases neurotransmitters such as serotonin, norepinephrine, and acetylcholine. Also, specific cells of the hypothalamus nucleus are activated to synthesize and secrete corticotrophin-releasing factors. At the end of this process, cortisol is the primary stress hormone, produced and secreted along with catecholamines released by the sympathetic nervous system. The psychological stress caused by this inappropriate response creates an emotional overload, which also reduces the processing power of the hippocampus, and mental and perceptual activities are reduced, resulting in fatigue. It can also be stated that noise leads to changes in the limbic system, the autonomic nervous system, and the neuroendocrine system [32, 36, 40-42].

As Table 5 displays, the greatest correlation between subjective and objective fatigue responses was observed for three scenarios of HTV (5 m/s2 rms - 31.5 Hz), HTV (10 m/s2 rms -31.5 Hz), and concurrent exposure to noise and HTV (10 m/s2 rms - 31.5 Hz). The absorption of vibration energy at high frequencies was limited in the primary tissues close to the vibration source (fingers, palms, and wrists), but HTV increases with the decrease in frequency and could be distributed and absorbed in the tissues far from the upper body vibrating source (arm, neck, and head) [13, 15, 43].

There are several limitations to this empirical study. First, the participants consisted of just males, so gender was not considered as a variable in the present study. Second, this research used short-term exposures while working hours are longer in the real world. Hence, further field studies with long-term exposures are recommended to be conducted. Besides, the biodynamic response functions of muscle may vary with different exposure scenarios. Finally, while it is challenging to consider all the possible combinations of these factors in the experiments, this study only considered some combinations of noise and vibration frequencies. It can also be due to not increasing the number of exposure scenarios and the possibility of losing participants. Moreover, the considered values are determined based on field data of jackhammer device exposure to noise and vibration.

Biodynamic factors such as body posture and coupling forces (grip and push forces) can be varied during work with vibrating hand-held tools [44, 45]. In this study, to investigate the interaction of noise and vibration simultaneously, these biodynamic factors were fixed in a recommended normal range of typical working with jackhammers. However, future studies should investigate the interaction effect of these physical variables of vibration and noise in different biodynamic conditions. The number of samples was limited to 40 participants. The cooperation of more workers to participate in the current study was impossible. They did not want to cooperate satisfactorily mainly because of interference with their working hours.

5. Conclusion

The present study produced new data on the interaction effect of noise and HTV on muscle and mental fatigue in a simulated work with building vibrating tools. This evidence can help set the dose-response threshold limit for co-exposures to physical stimuli in the workplace. The findings confirmed that concurrent exposure to HTV and noise could cause muscle fatigue, and the role of HTV in this context was stronger than that of noise. However, noise has increased the main effect of HTV on muscle fatigue. Being exposed to both HTV and noise could cause perceived mental fatigue, and the role of noise in this context was more dominant than HTV. Vibration has increased the main effect of noise on perceived mental fatigue. Vibration frequency is an effective factor in muscle and mental fatigue. By decreasing the vibration frequency with the same vibration acceleration value, the amount of muscle and mental fatigue increases. Generally, HTV is one of the most harmful factors in construction professions; concurrent with noise, it can cause muscle and mental fatigue in workplaces, endangering workers' mental and physical health. These findings can help occupational health experts adapt the existing physical agents' exposure limits to realistic conditions and update occupational health surveillance activities.

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