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ARTICLE

# Combined Effects of Exposure to Noise and Vibration on Human Postural Equilibrium under Simulated Driving Conditions

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**ABSTRACT**

There is little information about drivers' body balance responses to combined exposure of noise and vibration. To fill the gap, this study aims to investigate the combined effects of exposure to noise and whole-body vibration (WBV) on the body balance under simulated driving conditions. For this purpose, 30 male participants were exposed to noise level at 85 dB(A) and two vibration levels (0.87 and 1.3 $m/s^2$) in five sessions. The design of the study was repeated-measures, and it attempted to assess the effects of 40 minutes of exposure to noise and/or WBV. Moreover, the participants' fatigue was measured with the Borg scale (CR 10). The findings revealed there was a significant change in body sway after WBV and combined noise and WBV exposure ($p < 0.05$). However, no significant difference was found in exposure to noise alone ($p > 0.05$). The effect sizes of exposure to noise, WBV (1.3 $m/s^2$), and combined noise and WBV (1.3 $m/s^2$) on body balance were 0.035, 0.425, and 0.635, respectively. Also, single exposure to WBV caused more fatigue than single exposure to noise ($p < 0.05$). Combined noise and WBV exposure descriptively caused more fatigue in comparison with the influence of WBV alone. The study concluded that the combined effects of exposure to noise and vibration are more than the sum of them. So, some synergistic effects may be observed in human body balance. It is essential to increase drivers' awareness and revise current health care interventions about new possible effects of combined exposures.

**KEYWORDS**

Body balance; noise; whole-body vibration (WBV); fatigue; combined exposure

## 1 Introduction

Combined effects of occupational physical agents on workers have been more focused recently in occupational exposure assessments [1]. Occupational exposure to noise and vibration can cause different kinds of health effects such as hearing impairment, noise annoyance, physiological and behavioral responses, and even some safety consequences [2–4]. Some studies have also shown body balance disturbance in exposure to noise and vibration [5–7]. Balance or equilibrium, as an essential functional skill, can affect the human ability to do different daily activities. Balance refers to the complex task of the integration of multiple sensory inputs, including visual, vestibular, and somatosensory systems [8]. Postural control is generally identified by body sway that is calculated by measures of the center of pressure (COP) obtained from force plate data [9].

Considering the possible effects of noise exposure on body balance, Park et al. [5] reported that occupational exposure to noise, especially at high frequency, resulted in remarkable balance impairments. Sakellari et al. [10] also demonstrated that increased sound loudness affected human body balance adversely. In a similar vein, Chen et al. found that unpleasant auditory stimuli influenced human equilibrium and increased postural sway [11]. Furthermore, exposure to vibration, especially whole-body vibration (WBV), can affect body balance. Lu et al. [12] stated that WBV had adverse effects on body balance, particularly at the high frequency of WBV. Ahuja et al. and Oullier et al. also demonstrated that postural stability deficits occurred in occupational exposure to WBV [7,13].

It is noteworthy that some employees, like heavy equipment drivers, are mostly simultaneously exposed to multiple factors such as noise and WBV in real working conditions. Heavy equipment vehicles include a wide range of machinery such as different types of dozers, trucks, loaders, graders, power shovels, etc., that their operators can be exposed to considerable levels of noise and vibration. For instance, Legris et al. [14] revealed that the driver's daily exposure to noise was approximately 84 to 99 dB(A) in different types of heavy equipment vehicles. Likewise, Spencer et al. [15] indicated that noise exposures were 80 to 109 dB (A) among heavy equipment drivers. It is noteworthy that the American Conference of Governmental Industrial Hygienists (ACGIH) has recommended noise exposure limit of 85 dB(A) for worker's time-weighted average over eight hours per day [16]. Marin et al. [17] showed the average of three directions of WBV was from 0.38 to 1.47 m/s$^2$ in different types of vehicles in mining. Also, Mandal et al. [18] reported that drivers' WBV exposures were from 0.5 to 1.54 m/s$^2$ in opencast mine while the International Organization for Standardization (ISO 2631, R2004) has suggested an 8-hour occupational exposure limit of 0.87 m/s$^2$ for WBV [19].

One of the most significant consequences of body balance disturbance is drivers' falling from heavy equipment vehicles as a considerable non-traffic occupational damage [20]. According to a report from Washington State's trucking industry, the claimed cost average for falls was up to $66.900 million from 1997 to 2005 [21]. Shibuya et al. [22] stated that drivers' falling from heights was the most frequent accident around and on the trucks. They recognized the loss of body balance was one of the most influential factors in drivers' fall injuries. Moore et al. [23] found that most of the falls at mining activities generally happened during ingress and egress of the facilities such as wheel loaders, large trucks, conveyor belts, and dozers.

Most researches have traditionally focused on drivers' exposure to a single threatening physical factor. So, it is necessary to have a more comprehensive view of combined exposure to noise and vibration among drivers. Moreover, little information is available regarding drivers' body balance responses to combined exposure of noise and vibration. Thus, this study aims to analyze the combined effects of exposure to noise and WBV on the human body balance under simulated driving conditions. Also, it purposes to provide the opportunity to implement preventive health programs, and improve occupational health surveillance actions for drivers employed in mine and road construction.

## 2 Materials and Methods

### *2.1 Subjects*

A total number of 30 male subjects volunteered to participate in this study. The mean ± SD of age, height, and weight of the participants were 30.17 ± 3.94 (between 25 and 35) years, 1.76 ± 0.64 m, and 72.17 ± 10.27 kg, respectively. Also, the subjects' body mass index (BMI) average was 23.16 ± 2.39 kg/m$^2$. The participants had no history of possible medications related to body equilibrium. Also, they had no previous exposure to high levels of noise and vibration. The mean hearing thresholds of the participants were lower than 20 dB in the frequency range between 250 Hz and 8 kHz. The participants were required to get at least 7 h sleeping the night before each session, and not to use caffeine or any other stimulants. All participants were paid to ensure their motivation.

### *2.2 Apparatus*

As shown in Fig. 1, a vibration simulator machine located in the research laboratory of Hamadan University of Medical Sciences was used for simulating WBV exposure. This machine works with a pneumatic system mechanism, and it can produce vibration in different adjustable acceleration and frequency spectrum. Also, it can simulate actual driving conditions of heavy equipment in work environments such as mines or road construction.

**Figure 1:** Vehicular whole-body vibration simulator utilized for the experiment

The Kistler 9286BA force platform, Kistler 9865 amplifier, and Kistler 5691A Data Logger (Winterthur, Switzerland) were applied to collect outputs of COP at a sampling frequency of 100 Hz. The force plate signals were filtered with a low pass filter with a cut-off frequency of 5.0 Hz. The force plate outcomes were used to calculate COP parameters (The Antero-Posterior (AP) and Medio-Lateral (ML) coordinates) by formulae reported in the study by Cornelius [24]. The Root Mean Square (RMS) amplitude that characterizes the standard deviation (SD) of COP displacement was employed to measure the average absolute displacement around the mean COP.

For simulating noise exposure, a noise track which had been recorded previously in a bulldozer working in a mine was used. The noise track existed in the archive of Hamadan University of Medical Sciences media laboratory.

A spherical loudspeaker (OS003-BSWA Technology Co.) placed at the back of participants was employed to do noise emission. The average of the A-weighted equivalent noise level (LAeq) was 85 dB(A) for each session of noise exposure. All subjects were exposed to the same noise level.

### *2.3 Experimental Design*

The study was conducted using a within-subjects design, where all participants were considered as their own controls. A repeated-measures design was done to investigate the effect of an exposure of 40 min to noise and/or WBV in five different conditions: (1) noise exposure (Noise), (2) WBV (0.87 $m/s^2$) exposure ($WBV_1$), (3) WBV (1.3 $m/s^2$) exposure ($WBV_2$), (4) combined exposure to noise and WBV (0.87 $m/s^2$) (Noise+$WBV_1$), and (5) combined exposure to noise and WBV (1.3 $m/s^2$) (Noise+$WBV_2$). There were some reasons for choosing this exposure time (40 min) for each scenario. First, the pre-test sessions suggested that this exposure time can be appropriate. Second, longer exposure time might result in missing the participants during the study. Also, the noise level of 85 dB(A) and WBV value of 0.87 $m/s^2$ were determined according to ACGIH-TLV and ISO 2631(R2004) exposure limit recommendations [16,19]. Based on the real data obtained from mining drivers exposed to WBV, the acceleration value of 1.3 $m/s^2$ was also selected. It should be noted that the frequency spectrum below 10 Hz and Z-direction were the main frequency and direction of WBV exposure among most of the heavy equipment drivers [25]. Hence, the frequency of vibration was set at 5 Hz in the Z-direction for all WBV exposure conditions. The research was done in an air conditioning chamber with the dimensions of $L \times W \times H = 3.70 \times 2.40 \times 2.70$ m. The air velocity was set at 0.15 m/s, and the relative humidity was fixed at 50%. Besides, light intensity was equal to 500 lx, and the air temperature was kept constant at 22°C in each session. A total of five experimental conditions were performed by all participants randomly, with an interval of at least 24 h between the experiments to prevent any influences of the previous session. Subjects' COP was measured in ML and AP axes in two different vision conditions, including Eyes-Open (EO) and Eyes-Closed (EC) before and after the exposure in each session.

The Borg scale (CR-10) was used to determine the perceived fatigue of the participants [26]. The participants were instructed to rate the scale before and after 40 min of exposure to noise and/or WBV. The Borg scale is a numerical list from 0 to 10, with number 0 indicates nothing at all, and number 10 shows strongly extreme. It generally takes only some seconds for the participants to complete.

### *2.4 Procedure*

This study was approved by the Ethics Committee of Hamadan University of Medical Sciences (Ethic Code: IR.UMSHA.REC.1398.108). All participants were informed of the research, and the consent forms were obtained. The participants were asked to stand bipedal, upright, and barefoot on the force plate to measure their body balance. They stood with their arms hanging close to their body and looking directly to the opposite point. Also, the researcher asked them to keep their head in a forward-facing position and remain as motionless as possible before each exposure during the experimental sessions (Fig. 2).

Then, they were asked to perform six 10-second trials (three EO and three EC). In the EO trials, the participants were asked to stare at the front target placed at approximately 2 m from them. Then, the subjects got in the simulator machine and set its seat height, backrest, and steering wheel appropriately. Next, they were asked to put their hands on the steering wheel and start to drive as if they were driving real heavy equipment. For simulating driving, a recorded movie of the cabin of an actual driving heavy equipment was being played on a large screen TV in front of the participants (Fig. 1). The subjects were exposed to 40 min of exposure to noise and/or WBV while they were sitting on the vibration simulator. Noise level and WBV acceleration were being measured with SVAN 971 and SV 106A (Svantek, Poland), respectively to ensure that the participants were exposed to the same level of noise and WBV during the entire experiment. After the exposure, the subjects climbed down on the force plate without their feet touching the ground. Then the before-exposure protocol was run for collecting data to measure body balance. Fig. 3 depicts the different steps of the experiments.

**Figure 2:** Standing position on force plate before and after exposure sessions (Six trials consisted of three eyes open and three eyes closed)

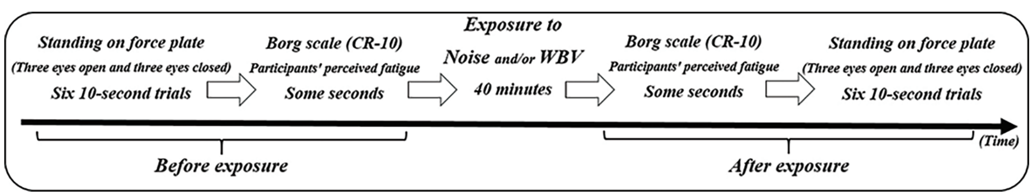


**Figure 3:** Flowchart of experiment setup

### *2.5 Statistical Analysis*

Before the analysis, the signals of the force plate were used to compute the RMS of COP. The COP in AP and ML directions was calculated by X and Y coordinates. Kolmogorov-Smirnov test was used to evaluate the normal distribution of the data. A paired sample *T*-test was run to assess the effects of exposure in each session. To compare different exposure sessions, the repeated measure ANOVA was employed. A Greenhouse-Geisser correction was applied when Mauchly's test showed sphericity violation, and the corresponding *p*-values were reported. Also, Tukey's test for Post-Hoc analysis was carried out to examine the mean differences. The effect size (ES) was also reported. All statistical analyses were run using SPSS-25. For all statistical analyses, $p$-value $< 0.05$ was considered to be statistically significant.

## 3 Results

Table 1 represents the mean differences and the standard deviations of RMS data of COP in AP and ML directions, and two vision conditions (EO and EC) during five sessions of exposure to noise and/or WBV.

**Table 1:** Mean differences of RMS data of COP in Anterior-Posterior (AP) and Medio-Lateral (ML) directions

| Vision | COP (mm) | Exposure conditions | | | | |
|---|---|---|---|---|---|---|
| | | Noise | $WBV_1$ | $WBV_2$ | Noise+$WBV_1$ | Noise+$WBV_2$ |
| | | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD | Mean ± SD |
| Eyes-Open | AP | 0.44 ± 2.38 | 0.62 ± 1.65 | 2.19 ± 2.60 | 0.67 ± 1.64 | 2.97 ± 2.29 |
| | ML | 0.23 ± 1.50 | 0.43 ± 1.44 | 1.49 ± 2.30 | 0.51 ± 1.44 | 1.71 ± 1.92 |
| Eyes-Closed | AP | 0.26 ± 2.26 | 0.33 ± 1.41 | 1.44 ± 2.20 | 0.57 ± 1.38 | 1.68 ± 2.37 |
| | ML | 0.14 ± 1.51 | 0.47 ± 1.34 | 0.90 ± 2.01 | 0.41 ± 1.39 | 1.21 ± 1.63 |

Note: WBV, whole body vibration ($WBV_1$: 0.87 $m/s^2$, $WBV_2$: 1.3 $m/s^2$).

Table 2 statistically compares the participants' body sway changes before and after exposure during all sessions. There was no significant difference between body sways before and after the Noise scenario ($p > 0.05$); however, significant differences were observed between body sways before and after exposure in other conditions ($p < 0.05$).

**Table 2:** The significant levels for changes of body sway before and after exposure in different conditions

| Vision | COP | Exposure conditions | | | | |
|---|---|---|---|---|---|---|
| | | Noise | $WBV_1$ | $WBV_2$ | Noise+$WBV_1$ | Noise+$WBV_2$ |
| Eyes-Open | Anterior-Posterior (AP) | 0.315 | 0.047* | < 0.001* | 0.033* | < 0.001* |
| | Medio-Lateral (ML) | 0.403 | 0.109 | 0.001* | 0.064 | < 0.001* |
| Eyes-Closed | Anterior-Posterior (AP) | 0.526 | 0.215 | 0.001* | 0.030* | 0.001* |
| | Medio-Lateral (ML) | 0.609 | 0.065 | 0.020* | 0.118 | < 0.001* |

Note: * Indicates statistically significant; WBV, whole body vibration ($WBV_1$: 0.87 $m/s^2$, $WBV_2$: 1.3 $m/s^2$).

As shown in Table 2, in $WBV_1$, there was a significant difference in COP-AP in the EO condition ($p < 0.05$). In Noise+$WBV_1$, significant differences were observed in EO and EC conditions except in COP–ML direction. In all situations, there were significant changes in body sway in $WBV_2$ and Noise+$WBV_2$ ($p < 0.05$). It was observed that $WBV_2$ and Noise+$WBV_2$ had more significant effects on participants' body balance compared with other conditions.

As illustrated in Table 3, there were significant differences in participants' body balance in all directions and vision conditions except in COP-ML in the EC ($p < 0.05$). It was observed that the subjects' body balance was affected more by the exposure to stimulus in the EO condition than in the EC.

**Table 3:** The significant levels for RMS data of COP in all directions and vision conditions

| Vision | COP | F | *p*-value |
|---|---|---|---|
| Eyes-Open | Anterior-Posterior (AP) | 8.367 | < 0.001* |
| | Medio-Lateral (ML) | 4.754 | 0.001* |
| Eyes-Closed | Anterior-Posterior (AP) | 3.109 | 0.018* |
| | Medio-Lateral (ML) | 2.136 | 0.081 |

Note: * Indicates statistically significant.

As represented in Fig. 4, the COP-AP and COP-ML mean differences were stronger in $WBV_2$ and Noise+$WBV_2$ in all sessions. It should be noted that mean differences of COP-ML were not significant in the EC condition in all exposure scenarios ($p > 0.05$). As can be seen, the mean differences of COP were not significant between $WBV_2$ and Noise+$WBV_2$ ($p > 0.05$). Also, the mean differences of COP were not significant between $WBV_1$ and Noise+$WBV_1$ ($p > 0.05$). However, body sway changes in $WBV_2$ were statistically stronger than $WBV_1$ ($p < 0.05$). Fig. 4 descriptively shows that Noise+$WBV_2$ influenced the subjects' body balance more compared with $WBV_2$. However, it was not statistically significant.

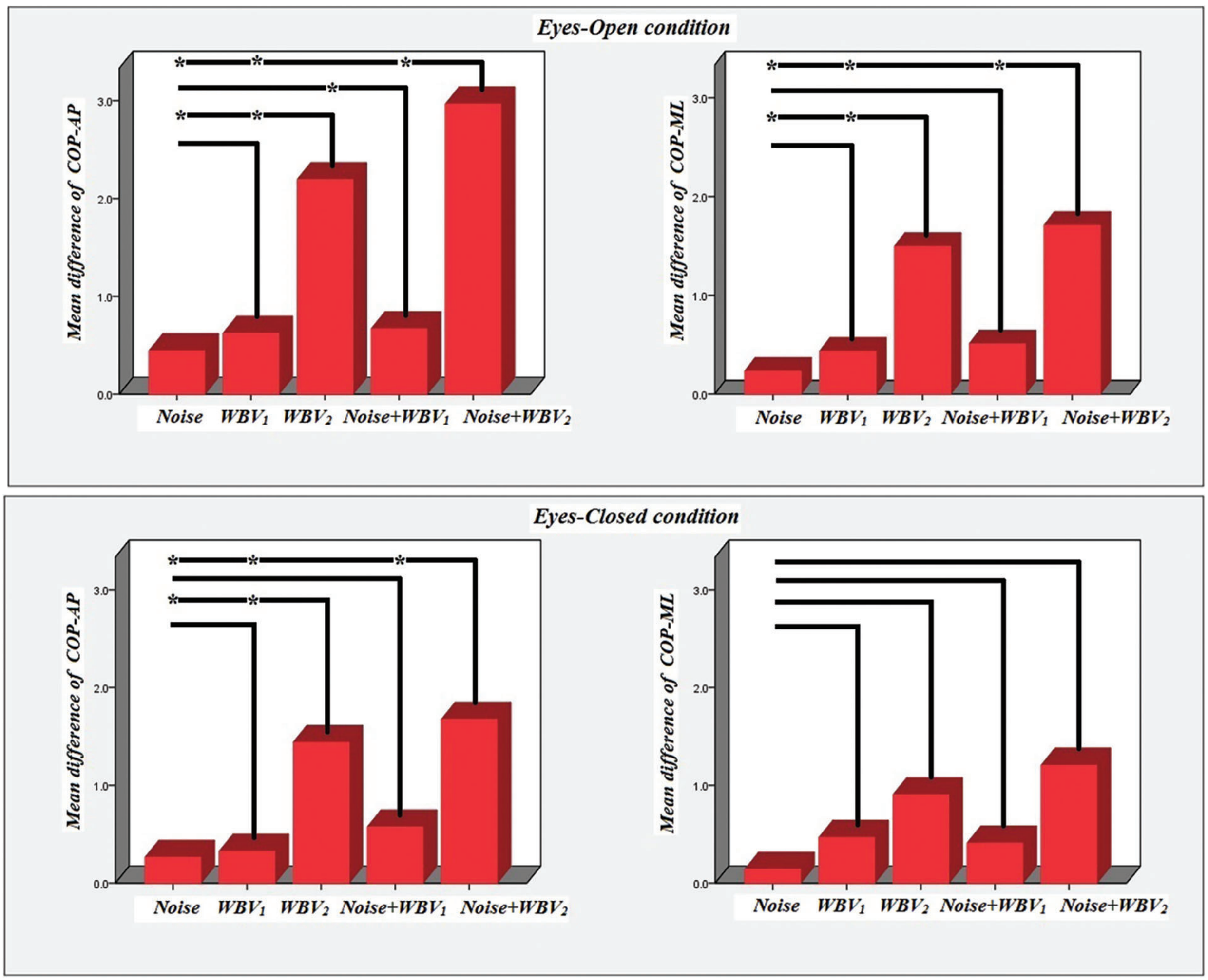


**Figure 4:** Mean difference of RMS data of COP in Anterior-Posterior (AP) and Medio-Lateral (ML) directions. Note: * Indicates statistically significant ($p < 0.05$)

Table 4 displays the pairwise comparisons and effect sizes of RMS data of COP in EO (AP and ML directions) and EC (AP direction) in different exposure conditions. As shown in Table 4, Noise+$WBV_2$, $WBV_2$, and Noise+$WBV_1$ had the strongest effects on the participants' body balance. It can be seen that the effect sizes of Noise, $WBV_2$, and Noise+$WBV_2$ on COP-AP were 0.035, 0.425, and 0.635, respectively. The combined effects of noise and vibration were more than the sum of these separated effects.

**Table 4:** Pairwise comparisons of RMS data of COP in all directions in different exposure conditions

| | COP | | Exposure conditions | | | | | ES | $p$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | Noise | $WBV_1$ | $WBV_2$ | Noise+$WBV_1$ | Noise+$WBV_2$ | | |
| Eyes-Open (EO) | Anterior-Posterior (AP) | Noise | – | 0.748 | 0.016* | 0.720 | 0.001* | 0.035 | 0.315 |
| | | $WBV_1$ | 0.748 | – | 0.011* | 0.913 | < 0.001* | 0.129 | 0.047 |
| | | $WBV_2$ | 0.016* | – | – | 0.011* | 0.158 | 0.425 | <0.001 |
| | | Noise+$WBV_1$ | 0.720 | 0.913 | 0.011* | – | < 0.001* | 0.147 | 0.033 |
| | | Noise+$WBV_2$ | 0.001* | < 0.001* | 0.158 | < 0.001* | – | 0.635 | <0.001 |
| | Medio-Lateral (ML) | Noise | – | 0.613 | 0.007* | 0.469 | 0.001* | 0.024 | 0.526 |
| | | $WBV_1$ | 0.613 | – | 0.038* | 0.832 | 0.003* | 0.086 | 0.215 |
| | | $WBV_2$ | 0.007* | 0.038* | – | 0.059 | 0.675 | 0.303 | 0.001 |
| | | Noise+$WBV_1$ | 0.469 | 0.832 | 0.059 | – | 0.020* | 0.114 | 0.030 |
| | | Noise+$WBV_2$ | 0.001* | 0.003* | 0.675 | 0.020* | – | 0.451 | 0.001 |
| Eyes-Closed (EC) | Anterior-Posterior (AP) | Noise | – | 0.898 | 0.046* | 0.523 | 0.033* | 0.014 | 0.609 |
| | | $WBV_1$ | 0.898 | – | 0.035* | 0.505 | 0.016* | 0.053 | 0.065 |
| | | $WBV_2$ | 0.046* | 0.035* | – | 0.109 | 0.700 | 0.306 | 0.020 |
| | | Noise+$WBV_1$ | 0.523 | 0.505 | 0.109 | – | 0.048* | 0.152 | 0.118 |
| | | Noise+$WBV_2$ | 0.033* | 0.016* | 0.700 | 0.048* | – | 0.340 | <0.001 |

Note: * Indicates statistically significant; WBV, whole body vibration ($WBV_1$: 0.87 m/s$^2$, $WBV_2$: 1.3 m/s$^2$); ES, effect size.

Based on repeated measurement ANOVA, there were significant differences in perceived fatigue among different exposure conditions ($p < 0.05$). However, pairwise comparisons showed that there was no significant difference in perceived fatigue between $WBV_2$ and Noise+$WBV_2$ ($p > 0.05$). In the current study, single exposure to the defined WBV levels caused more perceived fatigue than the exposure to the defined noise level ($p < 0.05$). As shown in Fig. 5, the mean difference of CR10 was more considerable in $WBV_2$ and Noise+$WBV_2$ compared with the other exposure scenarios. Also, the mean differences of CR10 were not significant between $WBV_2$ and Noise+$WBV_2$ ($p > 0.05$). Moreover, the Borg scales in $WBV_2$ was statistically stronger than $WBV_1$ ($p < 0.05$). The descriptive results showed that the combined noise and WBV exposure caused more fatigue than exposure to WBV alone.

## 4 Discussion

The combined effects of environmental factors on employees' health require much more attention from the experts in occupational health. As mentioned earlier, one of the main aims of this research was to help improve our understanding of heavy equipment drivers' exposure to combined noise and vibration. The findings of the study confirmed that exposure to noise and WBV had detrimental effects on the postural stability of participants in different exposure scenarios.

Some previous studies have shown that noise exposure affected postural control [5,10,11]; however, no considerable change was observed in the single noise exposure in this study. This finding is in line with what Mainenti et al. [27] and Palm et al. [28] found in their studies. Mainenti et al. [27] investigated the body balance of healthy subjects in exposure to different types of auditory stimulation. They found that there was no statistic difference between conditions with and without sound stimulation. So, it was concluded that balance may not be affected by the types of sound stimulation [27]. Also, Palm et al. [28] studied the effects of visual and auditory stimuli on the human postural stability. They concluded that auditory stimuli did not resulted in postural control impairements [28].

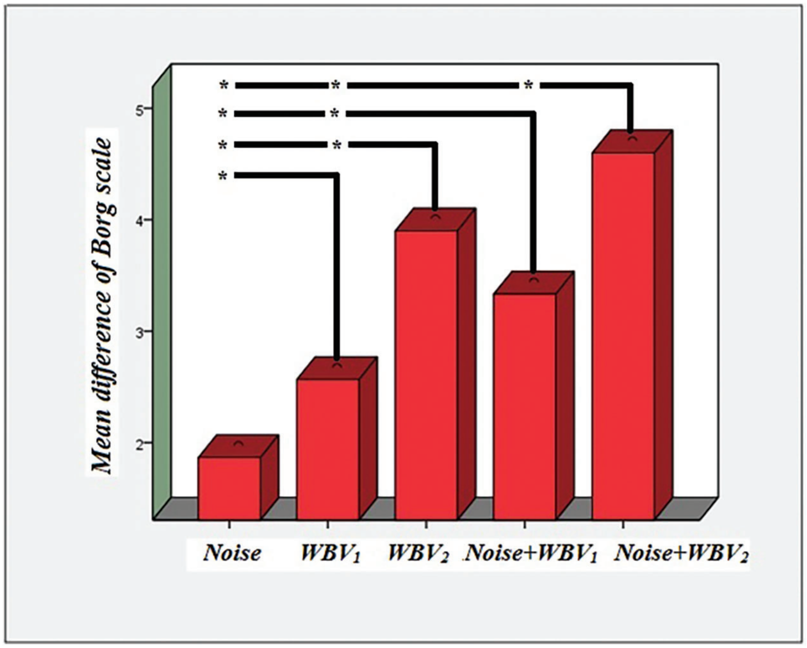


**Figure 5:** Mean difference of borg scale in all exposure conditions. Note: * Indicates statistically significant ($p < 0.05$)

Some reasons can be mentioned for this finding in the current study. First, the duration of noise exposure can affect participants' behavior [5]. Therefore, it seems that the considered noise dose (85 dB(A) for 40 min of exposure) was not adequate for observing noticeable body balance changes in exposure to noise alone in the current study. Besides, the possible compensatory role of the Central Nervous System (CNS) for deficits in vestibular system functions can become active during the experience of single exposure to noise [29,30]. Second, auditory stimuli are less influential in body balance in comparison with vestibular, visual, and somatosensory inputs [31]. Third, based on the literature, exposure to noise causes more body balance disturbance in individuals with NIHL [29,32]. Different senses like the vestibular system and proprioception can control postural stability. So, if they become impaired, auditory stimuli can increasingly affect postural stability [28]. Finally, all participants in this study were young and healthy without any possible medications related to body equilibrium. Young people can adapt their sensory system better to maintain their body balance against any environmental disturbance factors [30].

The results confirmed that WBV exposure can affect the participants' body balance considerably. The same findings were reported by some researchers like Ahuja et al. [7], Lu et al. [12], and Martin et al. [33]. Ahuja et al. [7] studied the effects of WBV on haul truck drivers in a "real-time" actual trucking environment. They concluded that exposure to WBV can influence the human body balance adversely.

Exposure to vibration can influence the human balance system, including muscles, visual, vestibular, and somatosensory systems [12,34]. Mani et al. [20] found some evidence of balance sub-system impairments as the consequences of exposure to WBV. However, Cornelius et al. and Santosa et al. did not find any WBV effects on body balance. It can be due to the differences in research methodology, vibration type, vibration dose, and human body balance indicators [24,35].

The current study findings confirmed that the vibration level is one of the main factors affecting body balance, especially in the AP direction. Generally, there are two different mechanisms identified for postural control in the AP and ML directions. While body balance is completely under ankle control in AP, it is controlled under the hip in an upright stance in ML [36]. Therefore, more significant differences in body sway in AP can be the consequence of more sensitivity of this direction to vibration [34]. Similar results can also be observed in other studies such as Ahuja et al. [7], Slota et al. [37], and Oullier et al. [38].

The vision was assessed in two conditions of EO and EC in this study. The visual information perceived from the environment, as one of the body balance sub-systems, can maintain body postural control. So, the EC condition can lead to higher body sway [8]. In the current study, the COP amplitude was more in the EC conditions. However, the mean difference between pre-exposure and post-exposure was higher in EO conditions in line with the findings of Halverson et al. [7,39]. It seems that exposure to WBV in EO can contribute to an incorrect perception of information that causes a deficit in body balance [7].

Also, the combined noise and WBV exposure showed more adverse effects on body balance compared with WBV exposure alone, which indicated that there are some interaction effects of noise and WBV on human body balance. Manninen et al. stated that body balance decreased more in the combined exposure to noise and vibration [40]. Also, Yilmaz et al. [29] proposed some synergistic effects of the combined exposure to noise and vibration on the vestibular system disturbances. In contrast, Bovonsunthonchai et al. [30] demonstrated that there were not any interaction effects of sound and vibration on body equilibrium. The authors mentioned that their method, sample size, and participants' ages could affect the results of their study.

It is difficult to make an accurate distinction between effect sizes of noise and vibration on the human vestibular system. Noise stimulates the vestibular system and results in balance impairments indirectly. Besides, vibration can cause deficits in body balance with affecting labyrinth mechanical trauma directly. Deficits in vestibular metabolism can be considered as another possible reason [5]. Combined exposure to noise and vibration can cause an additional burden on the exposed workers, which leads to inner ear disturbances [41]. Our findings revealed that exposure to noise, WBV, and combined noise and WBV caused fatigue in the participants. It is in agreement with other related studies such as Kjellberg et al. [42] and Satou et al. [43]. The most self-reported fatigue was associated with combined noise and WBV exposure. Fatigue decreases sensory input and motor output of the body balance system [44]. Therefore, it may be considered as one of the contributing factors to impaired postural balance [45,46].

Overall, this study attempted to describe some interaction effects of exposure to noise and vibration on human body equilibrium and fatigue. It also added new dose-response data of multiple exposures during simulated driving activity. As a practical note, postural stability is negatively influenced immediately after exposure to noise and WBV, which may increase non-traffic accident injuries such as falling and slipping among drivers. Hence, the first step in risk management is to increase drivers' awareness of the risk of body balance disturbances. Besides, it is recommended that drivers wait at least for a short time before getting out of heavy machines to reduce the consequences of body balance impairments. Moreover, to decrease the possibility of balance disturbance, mechanical vibration transmitted from heavy machines to drivers must be decreased as much as possible. Engineering technical methods and preventive maintenance programs should be applied.

There were some methodological limitations in the present study. First, there were just male participants in this study. So, gender was not considered as a variable. Second, the interpretation of the current results was limited by short-term exposure in comparison with actual working hours. Considering that drivers are exposed to noise and WBV up to 8 h a day in real workplaces, more studies with long-term exposures are suggested. Besides, more advanced psychophysiological methods are recommended for studying other interaction effects of exposure to combined noise and vibration. Visual disturbances can also be investigated in future noise and WBV studies on body equilibrium.

## 5 Conclusion

This study can provide some evidence of drivers' body balance impairments in exposure to combined noise and vibration. It is expected that these findings can improve occupational health surveillance actions for drivers working in the mines and road construction. The following conclusions were drawn from this research:

- Exposure to noise and WBV had detrimental effects on the participants' postural control in different scenarios of exposure. However, exposure to WBV could affect the participants' body balance remarkably in comparison with noise exposure.
- Exposure to noise and WBV had detrimental effects on the participants' postural control in different scenarios of exposure. However, exposure to WBV could affect the participants' body balance remarkably in comparison with noise exposure.
- The participants' body balance was affected by exposure to stimulus in the eyes-open condition more than in the eyes-closed.
- Exposure to noise and WBV produced fatigue in single exposure to noise or WBV and combined exposure to noise and WBV. It may also be considered as one of the influential factors in impaired postural balance.
- It is essential to increase drivers' awareness of new possible effects of exposure to vibration and employ technical engineering methods to reduce mechanical vibration in occupational health care programs.

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