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Seat suspension design for reduction of whole-body vibration of forklift drivers in warehouse

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ABSTRACT

Background: Whole-body vibration transmitted through the seat during forklift operation significantly contributes to musculoskeletal disorders among forklift operators.

Objectives: The study aims to design vibration absorbing materials for forklift driver seats and to compare whole-body vibration levels before and after implementing the new design

Methods: This study employed a quasi-experimental research design to compare whole-body vibration levels before and after the implementation of an absorption material in forklift seat design. The study population consisted 34 forklift drivers working in the warehouse department of an electronics manufacturing and assembly plant in Chachoengsao province. This experimental study was conducted over a seven-month period.

Results: The result of combination of butyl rubber sheets that were 25 x 25 x 1.5 cm in width, length and thickness, as well as layer 1 and layer 2 foam sponges that were 53 x 42 x 5 cm in size, improved the materials inside the seat. The measurement of the whole-body vibration exposure compared to the average period of 8 hours A (8) before and after the design of the vibration absorbing material inside the forklift seat showed significant differences in all three cases. While comparing the measurement group's vibration values to the ISO 2631-1, 1997 standard over an 8-hour period [A (8)], it was discovered that the vibration value exceeded the standard by 97.06% of 100% prior to design, and that the vibration exceeding the standard decreased to 50.00 percent of all measurements following design.

Conclusion: This study concludes that incorporating butyl rubber and foam sponge into forklift driver seats effectively reduces whole-body vibration transmitted through the seat during forklift operation.

Keywords: Forklift driver, Seat suspension, Whole body vibration

1. Introduction

Forklifts are extremely helpful and efficient machines design to help decrease or eliminate the risk associated with physical material handling by workers. Forklifts, however, could pose ergonomic risks, resulting in physical and mental exhaustion [1, 2], as well as musculoskeletal disorders (MSDs) [3]. This is primarily because forklift drivers frequently spend a considerable amount of their workday exposed to whole-body vibration delivered through the driver's seat [4].

MSDs are common occupational health problems among various types of vehicle operators, including forklift drivers, truck drivers, and heavy machinery operators [5-9]. Occupational health statistics showed that MSDs were the most common work-related ailments between 2019-2023. Over the past five years, an average of 3,765 occupational injury cases have been reported per year, accounting for approximately 0.90% of all workplace incidents [10].

Forklift drivers represent a high-risk occupational group for MSDs, primarily due to extended working hours combined with continuous exposure to vibrations transmitted through the forklift seat while transporting materials [11]. Vibrations caused by vehicle operation can harm various parts of the body, particularly the lower back, neck, and shoulders, which are the most commonly affected by MSDs [3, 12, 13]. Key factors contributing to the risk of MSDs among forklift drivers include improper sitting posture, prolonged static sitting, and seat designs that do not conform to the operator's body ergonomics. Whole-body vibration generated during forklift operation places additional biomechanical stress on the musculoskeletal system, which may lead to chronic disorders and ongoing discomfort [14].

The design of impact-absorbing systems to reduce vibration transmission, as well as alterations to sitting posture to match the worker's body ergonomics, are critical techniques for minimizing the onset of MSDs. Ergonomically constructed seats can greatly reduce vibration transmission to the body [15, 16] and reducing the risk of MSDs while also improving worker performance and efficiency [17].

2. Methods

2.1 Study area

The study was conducted in the warehouse department of an electronics assembly and manufacturing plant in Chachoengsao

Province. The study period was from February 2024 to August 2024.

2.2 Study Design

This was a quasi-experimental study which investigated the effects of whole-body vibration by comparing vibration levels before and after the use of a vibration-absorbing seat material for seated forklift operators. It also explored the association between whole-body vibration and the development of musculoskeletal disorder in forklift operators.

2.3 Sample Size and Sampling

The study included 38 warehouse forklift drivers and 2.5-ton sit-down forklifts. The sample size was determined using the objectives of designing a whole-body vibration absorbing material in a forklift seat for forklift drivers and comparing the whole-body vibration before and after constructing the forklift seat vibration absorbing material. The inclusion criteria for this study were forklift operators aged 18 years and older who voluntarily participate in the research, hold a seated forklift operator position, and possess a forklift driving license issued by the safety department. The exclusion criteria included employees with a history of accidents resulting in musculoskeletal disorders and those with pre-existing musculoskeletal disorders unrelated to forklift operation. The sample calculation employed a sample size calculation to compare the proportions of the population in the two sample groups that were not independent of one another. When the calculation is complete the minimum forklift drivers required was 29. This study accounted for a potential 10% loss in survey response from the subject group. Consequently, the researcher included all 34 employees in the study. Sample size was estimated using the following formula [18]:

$$n = \frac{N Z^2_{\alpha/2}[P(1-P)]}{[e^2(N-1)] + [Z^2_{\alpha/2} P(1-P)]}$$

where:

n= required sample size

N= total number of forklift operators in the warehouse department
(38 employees)

$Z_{\alpha/2}$ = standard normal value at a 95% confidence level (α=0.05), which equals 1.96

P= proportion of musculoskeletal disorders among forklift operators (0.25)

e= margin of error, set at 0.08

The values are substituted into the formula as follows:

$$n = \frac{38 \times 1.96^2[0.25(1-0.25)]}{[0.08^2(38-1)] + [1.96^2 \times 0.25(1-0.25)]}$$

$$n = 28.59$$

Thus, the minimum required sample size was 29 participants. To account for an estimated 10% non-response rate, the study included all 34 forklift operators in the research.

2.4 Data Collection

2.4.1 Whole-Body Vibration Meter

The vibration meters for measuring whole-body vibration (WBV) were installed in accordance with ISO 2631-1 standards [19], the vibration sensor is installed at the forklift seat. The measurement method is set to be perpendicular to the x-axis, y-axis, and z-axis according to the biomechanical coordinate system as shown in Figure 1. The calibration process followed rigorous procedures to ensure the accuracy of all equipment related to WBV measurement. Calibration of the sensors was essential for precise measurements which was also conducted following ISO 8041-2005 standards [20, 21]. The WBV analysis equipment used in this study is the SVANTEX model SV 106, which has been verified for accuracy prior to use in the research. Data collection was performed by measuring vibration before and after the design of vibration absorbing materials in forklift seats. The experiment involved three gathering cycles. First trial was while working in the morning before break, second trial was while working after the morning break and the third trial was while working before leaving work.

2.4.2 Satisfaction Questionnaire

Satisfaction questionnaire on forklift seat design to reduce the whole-body vibration exposure of forklift drivers. The satisfaction questionnaire was used to collect data both before and after the design of the vibration absorbing seat.

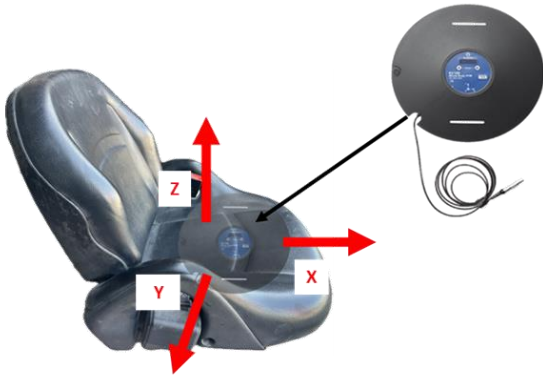

Figure 1: Installation of axial vibration sensor

2.5 Data Analysis

Data analysis was conducted using STATA version 18. Descriptive statistics were applied to examine frequencies, percentages, means, and standard deviations for general data, work-related information, and employee satisfaction after the seat redesign of implementation. Inferential statistics were utilized to compare before and after design. Paired t-test was used for normally distributed data, while the Wilcoxon signed-rank test was employed for non-normally distributed data.

3. Results

3.1 General and Work-Related Information

The majority of participants were male 88.24%, with female participants making up 11.76%. The average age was 38.29 years (SD = 8.41). The mean Body Mass Index (BMI) of the sample group was 23.31 (SD = 2.88), with most participants falling within the normal BMI range 67.65%. Regarding physical activity, 61.76% of participants reported exercising occasionally (1-2 times per week). The median forklift driving experience was 10.03 years (SD = 6.93), and the average working hours per day were 10.06 hours (SD = 0.97).

3.2 Design of Seat Suspension Materials in Forklift Seats

The design of the seat suspension material involved measuring the body dimensions of forklift operators in the warehouse department, alongside assessing the dimensions of the existing forklift seat. However, the researcher opted not to use the 95th percentile of body measurements to redesign the seat size, as the current seat already exceeds the width, length, and depth requirements of the 95th percentile of the sample group. Consequently, the existing seat structure could be used as a foundation for additional seat suspension material without compromising operator comfort.

A layer of butyl rubber, selected based on its capacity to reduce vibration within the frequency range of 25-250 Hz, was installed as the first layer. This layer measured 25 x 25 x 1.5 centimeters in width, length, and thickness. The second layer comprised the original foam sponge material, measuring 53 x 42 x 15 centimeters, which was retained in the seat.

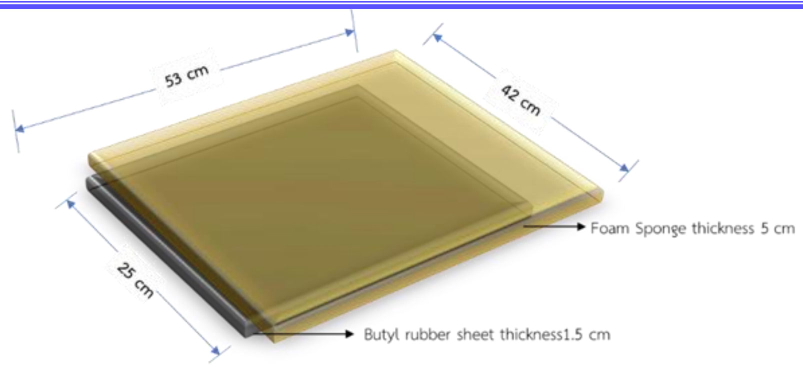

Figure 2: Width, length, and thickness of Butyl rubber sheet and Foam sponge

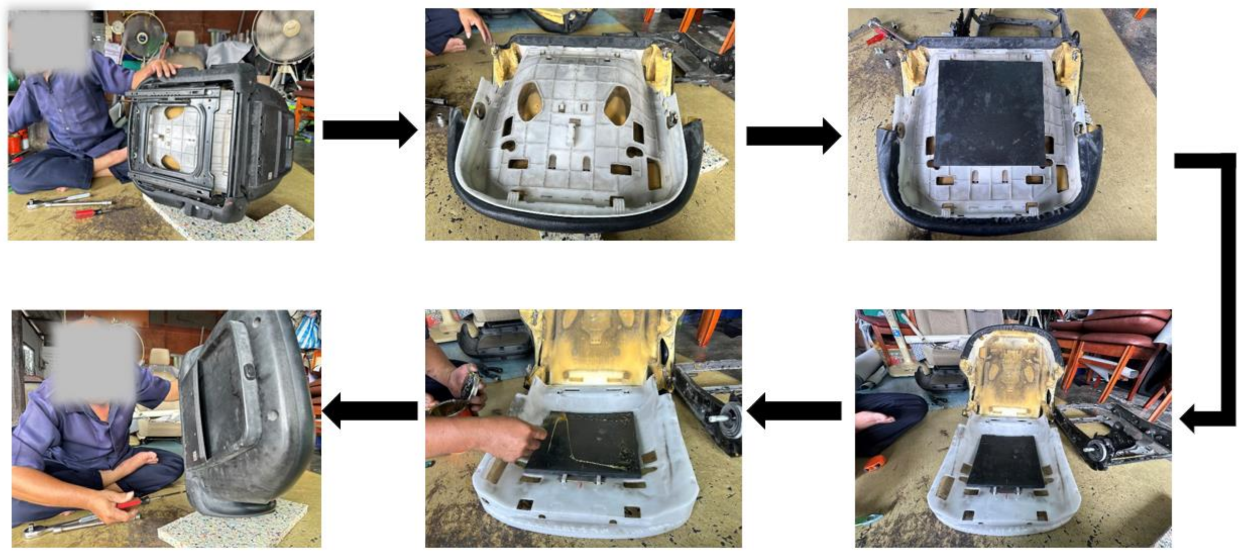

Figure 3: Butyl rubber sheet installation steps

3.3 Results of Vibration Measurements along the X, Y, and Z Axes

The whole-body vibration levels of forklift operators in the warehouse department were measured along the X, Y, and Z axes both before and after the seat suspension material was installed in the forklift seat. Average vibration values were calculated for each axis, based on the highest readings across three measurement trials. Among these, the Z-axis showed the highest vibration values, with 0.66 m/s^2 recorded before and 0.52 m/s^2 recorded after the seat suspension redesign. Upon comparing Z-axis vibration levels before and after the seat suspension design, the vibration level exceeding the safety standard decreased by 23.53% post-redesign.

3.4 Whole-Body Vibration Before and After Seat Suspension Design in Forklift Seats

Results of whole-body vibration exposure were used for comparison of whole-body vibration levels before and after implementing the seat suspension materials in the forklift seats of warehouse operators were conducted by analyzing the average vibration over an 8-hour workday or A (8) across three measurement trials. The results indicated a statistically significant difference in vibration levels before and after the seat suspension design.

For the first measurement trial, where data were normally distributed, a Paired t-test was used. The test showed a statistically significant difference in whole-body vibration levels before and after the design (P-value = 0.004). In the second trial, where data were not normally distributed, the Wilcoxon Signed-Rank Test was applied, also revealing a significant difference in vibration levels (P-value < 0.001). For the third measurement, with normally distributed data, a Paired t-Test was conducted, confirming a significant difference in vibration levels (P-value < 0.001) (Table 1).

Table 1: Comparative whole-body vibration (m/s^2) before and after the design of vibration-absorbing material in the forklift seat. (n=34)

Vibration [A (8)] Measurement	Median (IQR) Before	Median (IQR) After	Wilcoxon Signed-Rank Test p-value	$\bar{X}$ (SD) Before	$\bar{X}$ (SD) After	Paired t-test P-value
First trial while working before the morning break.	N/A	N/A	N/A	0.55 (0.09)	0.50 (0.05)	0.004*
Second trial while working after the morning break.	0.60 (0.54-0.65)	0.51 (0.46-0.54)	<0.001*	N/A	N/A	N/A
Third trial while working before leaving work.	N/A	N/A	N/A	0.60 (0.58)	0.50 (0.04)	<0.001*

*Significant at P-value<0.05

3.5 Satisfaction Before and After Seat Design for Whole-Body Vibration Reduction

The satisfaction of forklift operators regarding the seat suspension design for vibration reduction was evaluated both before and after the implementation. Results showed a statistically significant increase in satisfaction with seat cushion softness during use (P-value < 0.05), with the seat's ability to reduce vibration transmission to the body (P-value < 0.001), with the comfort of the backrest during forklift operation (P-value < 0. 05) and Overall satisfaction with the forklift seat (P-value < 0.001) (Table 2).

Table 2: Comparison of satisfaction before and after designing vibration-absorbing materials for forklift seats. (n=34)

Satisfaction Questions	$\bar{X}$ Before	$\bar{X}$ After	Mean Difference	95% CI	t-value	P-value
The width of the forklift seat is appropriate for the user.	4.62	4.65	-0.03	-0.21, 0.15	-0.329	0.744
The thickness of the forklift seat is suitable for use.	4.56	4.65	-0.09	-0.19, 0.01	-1.787	0.083
The depth of the forklift seat is suitable for use.	4.62	4.52	0.10	-0.07, 0.25	1.139	0.263
The comfort of the forklift seat material during use.	2.38	2.71	-0.33	-0.56, -0.08	-2.758	0.009*
The forklift seat can reduce vibrations transmitted to the body.	3.38	4.03	-0.65	-0.93, -0.36	-4.646	<0.001*
The cabin size of the forklift is adequate for use.	4.41	4.56	-0.15	-0.34, 0.05	-1.538	0.134
The comfort of the backrest while using the forklift.	3.38	3.65	-0.27	-0.46, -0.07	-2.721	0.010*
The height of the backrest is appropriate for forklift use.	3.94	4.09	-0.15	-0.30, 0.004	-1.968	0.057
Overall satisfaction with the forklift seat.	3.91	4.47	-0.56	-0.77, -0.35	-5.320	<0.001*

*Significant at P-value<0.05

4. Discussion

The study resulted in measurements of whole-body vibrations among forklift operators along three axes (X, Y, and Z) before the design of vibration-absorbing materials indicated that. The Z-axis had the highest vibration level, followed by the X-axis, and the Y-axis. After material adjustments, the Z-axis maintained its highest average vibration level, followed by the Y-axis and the X-axis which is consistent with the previous study found among rice harvester operators in Phayao province which showed the Z-axis having the highest average vibration level [22].

Similarly, the usefulness of seat cushions in reducing whole-body vibrations in forklift drivers at Bangkok Port was investigated using two types of seat cushions: one made of silicone rubber sheet and polyurethane foam, and the other made of butyl rubber sheet and polyurethane foam [10]. After utilizing the first type of seat cushion, the average value in the Z-axis was greater than the Y-axis and X-axis, respectively, whereas the latter type of seat cushion had a higher average value in the Z-axis than the Y-axis and X-axis. The majority of studies on whole-body vibration in drivers and operators of various types of machinery show that the Z-axis has a higher vibration value than the other axes [23, 24], which is caused by the impact and vibration force transmitted from the road surface through the wheels and suspension system up to the seat, where this force is transmitted in the vertical axis. Furthermore, the driver's posture, sits upright and transfers the weight of the body to the seat across the buttocks and pelvis, causes the vibration in the Z-axis to be communicated to the body more than other axes. Other factors that make more vertical impact than horizontal include uneven road surface conditions, vehicle speed and load weight [25]. A comparison of whole-body vibration levels with the ISO 2631-1(1997) standard found that vibration levels experienced by forklift operators prior to and following the design of vibration-absorbing materials in forklift seats exceeded the standard by 90.53% and 50.00%, respectively. This was consistent with the findings which examined whole-body vibration exposure and lower back pain among operators of vibratory piling machines used in riverbank reinforcement work in Ayutthaya province, with 86.67% of participants experiencing vibration levels over the standard recommended by 2631-1, (1997) [26]. Similarly, the study on the effectiveness of seat cushions in reducing whole-body vibration for sit-down forklift operators at a Bangkok port discovered that, prior to using seat cushions, all of participants experienced vibration levels that exceeded the standard [27]. Many studies have found that a population of heavy machinery operators and drivers was exposed to whole-body vibration levels that exceeded the permissible limits [28, 29].

Whole-body vibration exposure limit values A (8) was measured three times to assess the whole-body vibration exposure experienced by forklift operators before and after the use of vibration-absorbing materials is butyl rubber sheets in seat suspension. The study found significant reductions in whole-body vibration. This finding was consistent with previous studies on warehouse forklift operators who use seat cushions with specific dimensions in width, length, and thickness for the seat [15]. The study in warehouse department of forklift drivers [4] showed that designed seat cushion significantly reduced health-related vibration impacts and discomfort ($p<0.05$) which is reduced the A (8) vibration level from 0.1468 m/s^2 to 0.1291 m/s^2. That result was also support from seat cushions designed to reduce whole-body vibration among sit-down forklift operators at a port in Bangkok [26]. The vibration acceleration levels before using the cushions averaged 2.42 m/s^2 after using the same type of cushion (butyl rubber with polyurethane foam) the average vibration was decreased to 1.89 m/s^2 and when compared to baseline it was statistically significant differences.

The design and installation of vibration absorbing materials in forklift seats by using appropriate hydraulic dampers under and behind the forklift seats in this case could reduce the risk of injury from full body vibration by up to 60%. Moreover, the air cushion could reduce the amount of vibration transmitted to the forklift drive system [30]. Similarly, from the vibration test of forklift seats using two types of materials that showed that the air cushion seat was 22% more effective than the mechanical suspension [31]. Moreover, this study could indicate satisfaction with the design of forklift seats, as measured by the satisfaction level after designing the materials inside the forklift seats among drivers. The section of comfort of the forklift seat materials which can reduce vibrations transmitted to the body and the comfort of the backrest while using the forklift was the most satisfactory part.

5. Conclusion

The study concludes that the design of vibration absorbing material by installing the first layer of butyl rubber sheet into the forklift seat structure with the second layer of foam sponge material can effectively reduce the whole-body vibration received through the forklift seat to the forklift driver with statistically significant efficiency. The satisfaction questionnaire before and after the design found that in terms of the comfort of the forklift seat material during use, the forklift seat can reduce vibrations transmitted to the body and the comfort of the backrest while using the forklift, there was a statistically significant association.

However, other aspects that may factors the reduction of whole-body vibration levels from the design should be investigated by further studies, such as lift materials and other structures, human factors, and environmental factors.

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Author contributions

AK: Conceptualization, data curation, formal analysis, methodology, writing original draft, writing review and editing. VP: Conceptualization, supervision, writing original draft, writing review and editing. SC: Conceptualization, supervision, writing original draft, writing review and editing.

Declaration

Ethics approval and consent to participate

This study received human ethical approval from Khon Kaen University human ethic committee (HE662192). All the participants were fully informed regarding the study objectives and written informed. The written informed consent was received from participants before they entered into the study.

Competing interests

The authors declare no competing interests.

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