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Real-Time Simultaneous Vibrotactile Sensation on the Lower Limb for Drowsiness Prevention: An Exploratory Study

Raja Muhammad Hafiz Raja Md Zainuddin[a], Nor Kamaliana Khamis[a,b*], Nur Ezwanni Mohd Radzali[a], Norsuzlin Mohd Sahar[c], Mohd Faizal Mat Tahir[a,b], Nashrah Hani Jamadon[a], Zaliha Wahid[a], Dian Darina Indah Daruis[d] & Mohd Zaki Nuawi[a,b]

[a]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Malaysia*

[b]*Centre of Automotive Research, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, Malaysia*

[c]*Institute Climate Change, Universiti Kebangsaan Malaysia, Malaysia*

[d]*Department of Mechanical Engineering, Faculty of Engineering, Universiti Pertahanan Nasional Malaysia, Malaysia*

**Corresponding author: kamaliana@ukm.edu.my*

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ABSTRACT

Drowsiness is one of the contributing reasons to road accidents. So far, researchers and practitioners have undertaken many preliminary investigations to reduce drowsiness. Most of this research has mainly concentrated on evaluating drowsiness rather than preventing it. However, previous studies frequently neglected to analyze a diverse range of vibrotactile elements, such as frequency, waveform, and amplitude. As a result, there is a lack of knowledge regarding the most efficient vibration characteristics for preventing drowsiness. This creates an opportunity for more research to determine and enhance these elements for practical use. Hence, the purpose of this study is to determine the optimal vibration parameters for the vibrotactile system to stimulate drivers. This study developed four sets of different vibrotactile sensation systems to be tested on the participants. The results showed that most participants chose System 1 which offered vibration characteristics with the frequency at 125-140 Hz, 255 PWM amplitude, and sinusoidal signal type as the optimal vibrotactile system. It is expected that this study will benefit the road safety agency, vehicle manufacturer and help make cities safer and improve road safety.

Keywords: Microsleep; driving; vibration

INTRODUCTION

Drowsiness increases the likelihood of microsleep, which is also referred to as fleeting sleep. It is a phenomenon that many individuals regularly encounter unknowingly. This phenomenon refers to a condition as characterised by brief, irregular periods of sleep, temporary episode of sleep which may last from fraction of second to 15 seconds (Balaji et al. 2021). A poor sleep quality can caused microsleep (Cai et al. 2021; Hidalgo-Gadea et al. 2021). Previous research indicates that a warning system utilizing vibration or haptic feedback to elicit the driver's response can mitigate this issue. Fang et al. (2024) and Samsel et al. (2024) proved that the vibration system can effectively notify the drivers in any drowsy driving scenarios. Research conducted by Gaffary et al. (2018) indicates that drivers can respond to 0.3 seconds more swiftly when utilizing the vibrotactile system compared to the visual warning method. Laakmann et al. (2023) did a study on several modalities and demonstrated that the tactile modality is more effective as an alarm and can alert the driver. S. Saranya et al. (2023) and Zuki et al. (2016) also found that tactile modality is more effective than audio because there is a lot of noise in the surroundings while driving and the drivers cannot hear alarm.

Various past studies on vibrotactile systems in sending warning signals to drivers have been done and tested on several different mediums. Table 1 shows past studies in studying the delivery of warning signals on different medium. This type of medium can be divided into cloth, seat, pedals, seatbelt and steering. Although the objectives of each study are different, all these studies use vibrotactile systems to send warning signals through vibration directly to users.

TABLE 1. Previous studies have used vibrotactile on different mediums

No	Reference	Vibration Medium				
		Clothes	Driver Seat	Pedals	Seatbelt	Steering
1	Chang et al. (2007)		x			
2	Ji et al. (2008)		x			
3	Laakmann et al. (2008)		x	x	x	x
4	Morrell et al. (2010)		x			
5	Rahman et al. (2011)	x				
6	Ramalingam et al. (2017)		x			

Numerous research has been conducted on the driver's seat as a medium for vibration. The medium for implementing this vibrotactile system is selected based on direct interaction with greater or more frequent stimuli. For instance, research conducted by Ramalingam et al. (2019) examined the impact of vibration features on the driver's seat. The study's results indicate that the driver's seat area in constant contact with the human body is classified as a critical zone. Furthermore, the appropriate location for transmitting vibrotactile stimulation will be established by the distribution of elevated pressure from the body. In comparison to other anatomical regions, the buttock area experiences the highest pressure while seated, with the area beneath the thigh and below the knee also demonstrating notable pressure (Wennerholm et al. 2008).

Nevertheless, research on acceptable vibration characteristics is presently insufficient and constrained. This is because of several factors, including the driver's body and contact area. The intensity of the vibration is influenced by the body mass index, commonly referred to as BMI (Kyun et al. 2008; Pau et al. 2012). It also influences by type of the road (Lantoine et al. 2021). Individuals with a greater BMI are reported to detect low amplitude signals more frequently than those with a lower BMI (Duthoit et al. 2017). Previous study indicates that elderly individuals have a diminished ability to perceive signals compared to younger individuals, irrespective of amplitude (Duthoit et al. 2017; Lin et al. 2005).

The primary aims of this study are to ascertain the sensation produced by the vibrotactile device, determine the placement of the vibrating device on the cushion pad, and combine the vibrotactile system with the microsleep detection system. This study provides valuable insight by determining the optimum vibrotactile stimulation for driver in preventing drowsiness in a real time.

METHODOLOGY

OVERVIEW

The study is structured into three phases. The first phase is developing a basic vibration system to collect vibration attributes such as frequency, amplitude, and signal type to determine the optimal vibrotactile system. The decision to rely solely on tactile (haptic) input was guided by prior findings suggesting that combining multiple sensory stimuli, such as visual and audio cues, can negatively affect driver attention and lead to confusion (Chang et al. 2011). This study exclusively employed tactile stimulation due to its unique focus on vibration properties. In the second phase, the optimal placement of the vibrotactile actuator on the seat cushion is established, followed by testing the selected vibrotactile system and the sleep detection system in the third phase. Two distinct experimental sessions are carried out in the second and final phases to collect participant responses. These phases focus on determining the most suitable vibrotactile configuration, placing it correctly on the seat cushion, and evaluating its effectiveness alongside the microsleep detection system. Questionnaire outcomes were summarised using frequencies and percentages. To strengthen inference, 95% confidence intervals (CI) for key proportions were calculated using the exact (Clopper–Pearson) binomial method. Differences in selection frequencies across vibrotactile systems (System 1–4) and vibration locations (Location 1–4) were evaluated using a chi-square goodness-of-fit test (α = 0.05), with effect size reported as Cramér's V.

This work was designed as an exploratory or pilot study to identify promising vibrotactile parameter combinations and seat-pad placement prior to a larger confirmatory trial. Pilot-study guidance commonly recommends sample sizes in the 10 to 40 participant range to support feasibility objectives and obtain preliminary estimates with acceptable precision. Accordingly, 20 participants were recruited for Phase 1–2 to capture variability in perceived vibration across individuals (including BMI-related differences) and to provide reasonable precision for preference proportions. Phase 3 involved a more resource-intensive integrated simulator protocol, where microsleep detection, vibrotactile actuation and the reaction time logging). Therefore, a subset of 10 participants was used as a pragmatic pilot sample to verify end-to-end feasibility and generate preliminary reaction-time estimates to inform future power calculations. Pilot rules-of-thumb further support these ranges for early-stage studies. This selection is based on the potential suitability of experience and volunteering to do the experiment (DeFeo 2013). The adequate range of participants criteria for an experimental investigation was between 10 to 20 participants (Sekaran & Bougie 2016). In order to conduct research in the field, the factor of the number of participants should be considered so that the statistical analysis process can be carried out. A study from Guest et al. (2017) stated that the involvement of six to twelve individuals is sufficient to give significance to the findings.

FIRST PHASE

This phase involves gathering participant questionnaires about the suitability of various vibrotactile systems while conducting driving simulations, and at the end of this phase, the best combination of vibration parameters based on participant feedback will be chosen as the vibrotactile system in this study. Initially, several vibrotactile systems with various parameter combinations will be created. Table 2 shows the use of many electronic components to construct a vibrotactile system as well as a sleep detection system. Figures 1 and 2 show the circuit connections for the electronic components applied.

TABLE 2. List of components

No	Components
1	Arduino UNO
2	Breadboard
3	Jumper wire
4	Potentiometer
5	Transceiver module NRF24L01 RF24
6	Ultrasonic sensor HC-SR04
7	Vibration module

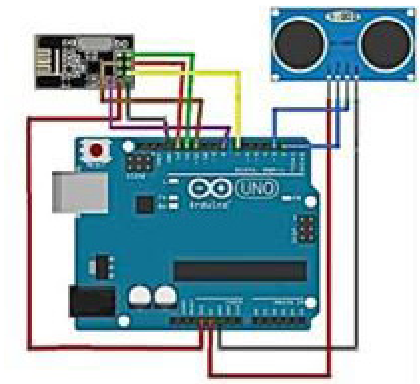

FIGURE 1. Vibrotactile circuit connection

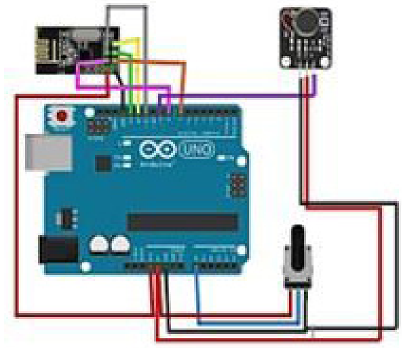

FIGURE 2. Microsleep detection circuit connection

Then, each system will be tested on 20 participants. This test will last for 15 minutes for each participant and will be carried out using a simulation like Figure 3 to get real seats and guarantee the safety of the participants. A total of 20 participants of different demographics will be selected to undergo this test. When undergoing the test, each participant is required to fill out a questionnaire that has been prepared through "Google Forms". Table 3 shows the main sections of the questionnaire. This test was conducted by using a simulator or a Perodua-type vehicle as shown in Figure 3.

FIGURE 3. Driving simulator preparation

TABLE 3. Main sections of the questionnaire

No	Sections
1	Participant demographics
2	Vibration strength (Slow/Medium/Strong)
3	Vibration comfort (No change/Comfortable/ Uncomfortable)
4	Appropriate vibration location selection
5	Suitable system to prevent microsleep
6	Perception of this trial in the prevention microsleep

SECOND PHASE

The second process involves deciding where to place the vibrator on the vehicle's cushion padding. Figure 4 depicts four spots on the cushion pad where this vibrotactile device can be placed. Locations such as the thighs and buttocks were chosen based on the distribution of high pressure when in contact with the human body. The participant's BMI will be measured initially because it influences how they feel about an individual's vibration. The second and third phases will be completed simultaneously. Each participant will also complete a questionnaire using the "Google Form" given. Participants were asked to complete the vibration strength scale at each tested location to find the best position for the vibrator. Table 4 displays the position of the tested vibrotactile system.

TABLE 4. Vibrotactile systems location

Location	Vibrotactile placement
1	Under the right thigh
2	Under the right buttock
3	Under the left thigh
4	Under the left buttock

FIGURE 4. Vibration location on the seat pad

THIRD PHASE

This phase is the last phase where the effectiveness of the selected vibrotactile system will be tested with the microsleep detection system developed in the previous study. A total of 10 participants will be tested by playing a driving simulation for 20 minutes. Then, each participant was also asked to fill out a questionnaire about the vibrotactile system that had been selected for the prevention of falling asleep for a moment. Figure 5 shows the flow chart of this phase and Figure 6 shows the driving simulation used. The straight and long road scenario is selected by setting the vehicle speed at 50 km/h up to 60 km/h.

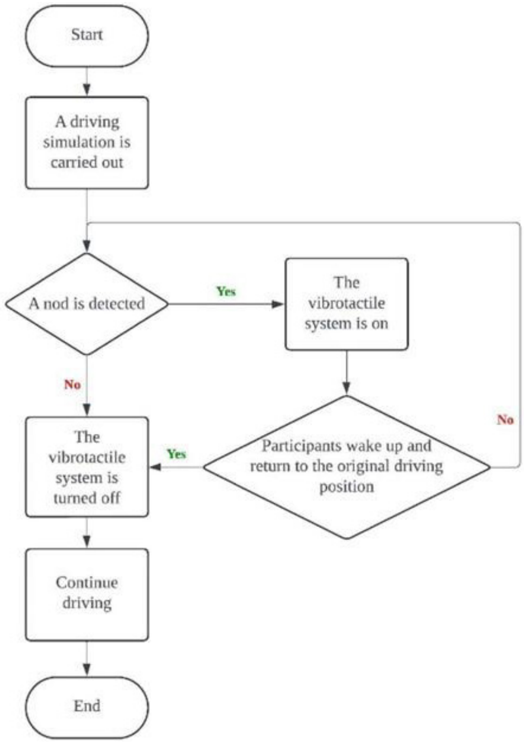

FIGURE 5. Flow chart of third phase

FIGURE 6. Driving simulation

RESULTS AND DISCUSSION

OVERVIEW

The study's findings pertain exclusively according to each stage. The study's results were derived from a questionnaire administered to 30 individuals, of whom 20 were evaluated in the first and second stages, while only 10 were selected to engage in a driving simulation utilising a vibrotactile system integrated into the seat.

DETERMINATION OF VIBRATION PARAMETERS

Four fundamental vibration systems have been built utilising the electrical components outlined in the methodological study for the determination of the vibration parameters of the vibrotactile system. The frequency, amplitude, and kind of vibration signal are documented. Vibration frequency measurements are obtained via a Vibrometer. According to Rao (2017), vibrometers are able to analyze frequency through the Fourier Transform (FFT), that decomposes the vibration signal into its respective constituent frequencies. To help identify the critical vibration modes, the frequency spectrum is displayed on the screen. Besides, the vibration amplitude can be regulated by the Pulse Width Modulation (PWM) technology, which governs the power supplied to the vibrator. However, the Arduino UNO microcontroller uses only 8-bit resolution. 8-bit microcontrollers consume less power than 16-bit or 32-bit, affordable and it is sufficient enough for most applications including motor control, sensor data processing and LED displays (Organtini 2015). The binary calculation on this 8-bit to represent the value 0 to 255 only. This means each data unit consists of 8 bits, allowing for 2^8 (256) possible values, ranging from 0 to 255 (Organtini 2015). The signal type will thereafter be identified via system programming utilising the Arduino IDE software. There are two sorts of signals: sinusoidal and shock.

A sinusoidal signal oscillates constantly, but a shock signal oscillates at a two-second interval. Drivers generally favor longer vibration durations (around 3 seconds), but they do not prefer extended intervals between vibrations (2 seconds) when used as seat-based rhythmic feedback (Ji et al. 2010). Furthermore, tactile signals with shorter inter-pulse intervals (IPIs) tend to create a stronger sense of urgency and enable faster reaction times. Therefore, IPI is a critical factor in designing alarm signals that demand immediate operator response to prevent adverse outcomes (Chancey et al. 2014). Table 5 shows the vibration parameters for each system.

TABLE 5. Vibration parameters of the vibrotactile system

No	Sections	Amplitude (PWM)	Signal types
1	125 - 140	255	Sinusoidal
2	70 – 90	170	Sinusoidal
3	135 – 160	255	Shock
4	75 - 105	170	Shock

SELECTION OF THE OPTIMAL VIBROTACTILE SYSTEM

All developed systems were tested on 20 individuals and evaluated by them. Based on the evaluation in Table 6, up to 65% of all participants preferred System 1, while up to 35% identified System 3 as the best vibrotactile system. This pick is based on the perceptions of each participant, who comes from various BMI groups. BMI has an impact on the human body's ability to detect vibrations (Duthoit et al. 2017).

In this sample, the distribution of preferred systems was not uniform across the four options ($\chi^2(3) = 23.60$, $p < 0.001$; Cramér's $V = 0.63$), indicating a clear preference pattern. System 1 was selected by 65% (13/20) with an exact 95% CI of 0.41–0.85, while System 3 was selected by 35% (7/20) (95% CI 0.15–0.59). No participant selected Systems 2 or 4.

TABLE 6. Selection of the optimal vibrotactile System

Types of system	Percentage (%)
System 1	65
System 2	0
System 3	35
System 4	0

SELECTION OF VIBRATION LOCATION

Based on the four vibration locations proposed in the study method, only one location was selected as an effective vibration location. Based on the participant's view of the vibration intensity at each location that has been tested with all four vibrotactile system, this selection was made. The results of the questionnaire found that all the participants felt a stronger vibration at location 2, which is at the buttocks compared to other locations. In addition, the participants also stated that the vibration was less felt in the third location which is on the lower part of the thigh. According to a previous study on pressure distribution in seats, higher pressure on the lower buttocks will indicate a direct contact area between the larger human body and is categorized as a critical zone (Ramalingam et al. 2019). Based on the questionnaire conducted, as many as 60% chose location 2, 20% chose location 3, 15% chose location

4, and 5% chose location 1. Therefore, location 2 shows that vibration stimulation can be transferred more effectively compared to other locations. Table 7 shows the results of the questionnaire regarding the selection of vibration locations.

TABLE 7. Selection of vibration location

Types of location	Percentage (%)
Location 1	5
Location 2	60
Location 3	20
Location 4	15

THE EFFECTIVENESS OF THE VIBROTACTILE SYSTEM IN PREVENTING MICROSLEEP

The effectiveness of the chosen vibrotactile system placed at location 2 was tested together with the microsleep detection system developed in a previous study. To determine the effectiveness of the vibrotactile system, the participants were ensured to feel the vibration on the cushion pad as soon as the nod of the head was detected by the short sleep detection system. The results of the participants' feedback showed that all participants felt the vibration when the head nod was detected by the short sleep detection system as shown in Figure 7. Detection systems for drowsy systems to reduce drowsiness are required to enhance safety (Bando et al. 2017). In addition, the time a response is taken when the vibrotactile system begins to vibrate until the system. The response time can be seen on the Arduino IDE software monitor. The majority of participants in this test required only one to three seconds to react or return to their normal driving posture after getting a vibration on the cushion pad. The reaction time in Phase 3 with range 1 to 3 seconds, indicating a rapid corrective response following vibrotactile activation. Reaction time was measured consistently for all participants using the same onset timestamp (vibration start) and response timestamp (observed correction) during the simulator session. The reaction time is shown in the red box in Figure 8. The reaction time is measured from when the vibrotactile system begins to vibrate until it stops. The findings of this study are nearly identical to the findings of Morrel et al. (2021), who discovered that drivers who utilize the vibrotactile system react 3.8 seconds faster than drivers who do not use it. This demonstrates that the chosen vibrotactile device can help to awaken a tired driver.

FIGURE 7. Result of the effectiveness of the vibrotactile systems in preventing microsleep

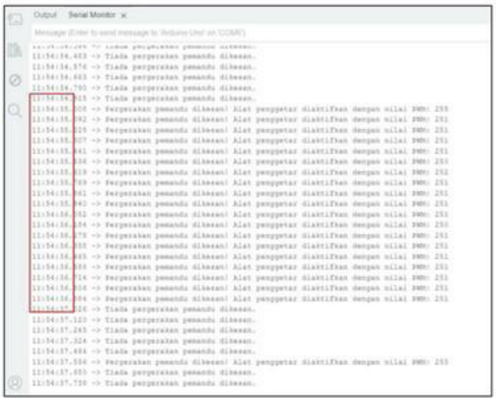

FIGURE 8. Participant reaction time

CONCLUSION

To ascertain the most effective vibration parameters, numerous participants selected System 1, characterized by a frequency of 125-140 Hz, a PWM amplitude of 255, and a sinusoidal signal type, as the ideal vibrotactile system. The vibration site was selected on the right buttock. The combination of the vibrotactile system and the microsleep detection system has demonstrated efficacy in transmitting warning signals to avert microsleep, based on the selection of System 1 and the vibration's position on the right buttock. The aim of this study is to mitigate drowsiness to decrease the incidence of traffic accidents. This study is anticipated to assist the Department of Road Transport in enhancing road safety and advancing Sustainable Development Goal 11 (Sustainable Cities and Communities), which seeks to create safer urban environments and improve road safety. This study was intentionally exploratory and used a relatively small sample, particularly in Phase 3. As a result, statistical precision is limited and the findings should be interpreted as preliminary, reflecting preference patterns and feasibility under a controlled simulator context rather than definitive population-level effects. Larger and more diverse samples, repeated-drive sessions, and (where feasible) on-road validation are recommended to confirm the generalisability of the identified parameter set and the placement, and to quantify effectiveness outcomes with adequate statistical power.

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DECLARATION OF COMPETING INTEREST

None.

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