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EXPOSURE TO WHOLE-BODY VIBRATION IN FORWARDER OPERATORS IN EUCALYPTUS HARVESTING

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Resumo

Exposição à vibração de corpo inteiro em operadores de forwarder na colheita de Eucalyptus. A extração mecanizada de toras na colheita de madeira pode causar exposição à vibração de corpo inteiro (VCI) e diversos problemas de saúde aos operadores. Nesse contexto, o objetivo deste estudo foi avaliar os níveis de exposição à VCI na extração de toras utilizando um forwarder que atuava nos turnos diurno e noturno e considerando diferentes elementos do trabalho. O estudo foi realizado em uma empresa florestal no sul do Brasil que realizava a colheita de povoamentos de eucalipto. Realizou-se um estudo de tempos considerando cinco elementos de trabalho: viagem vazio, carregamento, viagem carregado, descarregamento e tempos não produtivos. Os dados de vibração foram obtidos utilizando um medidor de VCI com um acelerômetro triaxial (eixos x, y e z) instalado no assento da máquina. Para avaliar a VCI, foi utilizado o método proposto pela Norma Brasileira de Higiene Ocupacional (NHO 09), calculando a aceleração resultante da exposição normalizada (aren) e o valor de dose de vibração resultante (VDVR). Os valores médios dos tempos consumidos com as atividades parciais foram comparados pelo teste de Tukey ($\alpha \leq 0{,}05$). A exposição ocupacional à VCI em operadores de forwarders (aren 0,85 e 0,78; VDVR 18,7 e 18,8 para turnos diurnos e noturnos, respectivamente) ficou abaixo dos limites considerados emergenciais (aren 1,1 e VDVR 21), porém medidas preventivas se mostraram necessárias para evitar níveis crescentes. Os elementos de trabalho mais prejudiciais do ciclo operacional, em termos de exposição à VCI, foram aqueles em que o forwarder se locomoveu no povoamento, ou seja, viagens vazio e carregado.
Palavras-chave: colheita de madeira; vibração ocupacional. ergonomia; máquinas florestais; saúde.

Abstract

Mechanized log extraction in wood harvesting can cause exposure to whole-body vibration (WBV) and several health problems for operators. In this context, the aim was to assess the levels of exposure to WBV when harvesting logs using a forwarder who worked day and night shifts and considering different elements of the work. The study was carried out in a forestry company in Southern Brazil that harvested eucalyptus stands. We conducted a time study considering five work elements: empty trip, loading, loaded trip, unloading and non-productive time. Vibration data was obtained using a WBV meter, with a triaxial accelerometer (x, y and z axes) installed inside in the seatpad of the machine. To assess the WVB, the method proposed by the Brazilian Occupational Hygiene Standard (NHO 09) was used, calculating the acceleration resulting from normalized exposure (aren) and the resulting vibration dose value (VDVR). The average values of the times consumed with the partial activities were compared by the Tukey test ($\alpha \leq 0.05$). Occupational exposure to WBV in forwarder operators (aren 0.85 and 0.78; VDVR 18.7 and 18.8 for day and night shifts, respectively) was below the limits considered emergency (aren 1.1 and VDVR 21), however, preventive measures were shown to be necessary to avoid increasing levels. The most harmful work elements of the operational cycle, in terms of exposure to WBV, were those in which the forwarder moved around the stand, as empty and loaded trips.
Keywords: wood harvesting; occupational vibration; ergonomics; forest machines.

INTRODUCTION

The Brazilian forestry sector contributes to the country's economic, social and environmental development. In 2023, with a total of 10.2 million hectares planted predominantly with *Eucalyptus* and *Pinus* sp., the sector represented approximately 7.0% of the Industrial Gross Domestic Product, provided 3.8 million jobs and helped preserve native forests (IBÁ, 2024). At the same time, the high demand for forest products has boosted the use of mechanized working operations, mainly in wood harvesting activities, in order to obtain high productivity, low production costs and safety and health for forest workers.

In Brazil, the main wood harvesting systems used are Cut-To-Length (CTL) and Full Tree (FT). The first refers to the cutting of trees (felling, delimbing, tracing and stacking), usually carried out by a harvester at the stump area, followed by the extraction of logs from the interior of the forest by a forwarder. In the second, the trees are felled by a feller buncher inside the forest and then skidded to the roadside by a skidder for further processing by the processor harvester (MACHADO *et al.*, 2014). The ergonomic characteristics of wood harvesting have improved over the years, primarily due to the mechanization of operations, which were previously performed using motor-manual methods with chainsaws. Under those conditions, working with chainsaws required high physical effort, involved maintaining improper postures, and exposing workers to elevated levels of noise and hand-arm vibration (MENDES *et al.*, 2019). Although forest machines have improved ergonomic conditions compared to chainsaws, operators are now exposed to increased repetitive movements due to joystick use, poor postures caused by seat design, and whole-body vibrations (WBV), typically resulting from operating conditions (JACK *et al.*, 2008; ØSTENSVIK *et al.*, 2008).

Operations with wood harvesting machines can cause exposure to WBV and cause several health problems, such as low back pain, musculoskeletal disorders and digestive problems (PHAIRAH *et al.*, 2016). In addition, high levels of WBV can negatively affect operational performance, particularly during tasks involving crane and grapple handling (HÄGGSTRÖM *et al.*, 2019). Therefore, the measurement of WBV exposure levels is important for attending several work laws, such as compliance with the program for the prevention of environmental risks (required for the Regulatory Standard - NR 9), verification of unhealthy work (required for the Regulatory Standard - NR 15) and attendance to the ergonomic program demanded for the Regulatory Standard - NR 17. Thus, studies on WBV in workstations in forest machine cabins are necessary in order to prevent the emergence of occupational diseases.

This study hypothesized that WBV exposure levels vary among forwarder operators depending on the specific work element and shift, given that operations take place on terrain with natural obstacles (e.g., branches, stumps, stones, holes, and leftover logs) and that operator visibility may be reduced during night shifts. Therefore, the objective was to evaluate WBV exposure during mechanized log extraction using a forwarder operating in both day and night shifts, considering different work elements.

MATERIALS AND METHODS

Characterization of the study area

The study was conducted in a forestry company located in Southern Brazil, where wood from planted forests was produced to supply the medium-density fiberboard (MDF) manufacturing sector. The forest stands were composed of *Eucalyptus grandis* and *Eucalyptus urophylla* × *E. grandis*, with 8 years old, planted in gently sloping terrain (3 to 8%) with planting spacing of 3 m × 2 m and individual average tree volume of 0.4 m³. The logs were produced in assortments of 2.40 in length and 15 to 17 cm in the small end diameter, 2.60 m in length and between 18 and 22 cm in the small end diameter, and 2.55 m in length and more than 22 cm in the small end diameter. The soil type was classified as Red-Yellow Argisol. During data collection, no rainfall was recorded, and temperatures ranged between 18°C and 22°C.

Wood harvesting system and evaluated machine

The study was conducted using wood harvesting machines operating under a cut-to-length (CTL) system in a clear-cut regime. Felling operations were performed by a harvester, which felled, delimbed, debranched, and processed logs at the stump area. Subsequently, the logs were extracted from within the stand to the roadside using a forwarder. The forwarder evaluated had an engine power of 200 kW, 8-wheel drive (8WD), and was equipped with a crane and grapple. Its dimensions were 10.8 meters in length, 3.1 meters in width, and 4.0 meters in height. At the time of data collection, the machine had accumulated 11,000 operating hours.

Characteristics of the sampled population and work shifts

The sample consisted of four male operators, with an average age of 40 years and 13 years of experience. Their average height was 1.66 meters, and their average body weight was 87 kilograms. Evaluations were conducted during both the daytime (8:00 a.m. to 12:00 p.m.) and nighttime (8:00 p.m. to 12:00 a.m.) shifts.

The study was initially submitted for analysis by a Research Ethics Committee (COMEP), approved under opinion number 2451557, with operators participating voluntarily and receiving clarifications through reading and signing the Free and Informed Consent Form (TCLE) in compliance with Resolution No. 196/1996 of the National Commission for Ethics in Research (CONEP) of the Ministry of Health of Brazil.

Time study

The time study was executed by the method of continuous timing, with a centesimal stopwatch and precision in seconds, considering five work elements of the operational cycle (Table 1). In addition, a pilot study was carried out in order to define the number of work cycles to be recorded (n), being calculated using equation (1), as proposed by Murphy (2005).

$$n = \frac{t^2 \times Var(WCT)}{\left(E \times \frac{WCT}{100}\right)^2} \quad (1)$$

Where: *t* is Student t value, *Var* (*WCT*) is variation of the operating cycle time, *E* is allowable error limit, % (it was considered 10%) and (*WCT*) is the average time of the work cycle, in seconds.

Table 1. Partial activities of the forwarder operating cycle.
Tabela 1. Atividades parciais do ciclo operacional do forwarder.

Work elements	**Description**
Empty trip	Time consumed driving the forwarder with the empty cargo box from the roadside to the inside of the stand next to the first pile of logs to be loaded.
Loading	Time consumed with the movement of the crane and loading of the machine's cargo box, including the driving between the wood piles for loading.
Loaded trip	Time consumed driving the loaded forwarder from the inside of the stand to roadside.
Unloading	Time consumed with the movement of the crane and loading of the machine's cargo box until complete emptying.
Non-productive time	Time consumed with operational and non-operational interruptions, which referred to machine stops and their respective causes: filling the checklist, filling the machine, communicating with a supervisor, personal breaks, among others.

Measuring whole-body vibration exposure levels

To assess WBV, the study followed the methodology outlined in the Brazilian Occupational Hygiene Standard NHO 09 (FUNDACENTRO, 2013). This is the most current standard for WBV assessment in Brazil, developed based on several international guidelines, including ISO 2631-1 (1997) – Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration. Part 1: General requirements and ISO 8041 (2005) – Human response to vibration – Measuring instrumentation.

The acceleration values were obtained using a *Brüel and Kjäer* 4447 whole-body vibration meter model, with a triaxial accelerometer (x, y and z axes) and DeltaTron Seat Pad Accelerometer Type 4515- B-002. Thus, it was possible to calculate the acceleration resulting from normalized exposure (aren) (Equation 2) and the resulting vibration dose value (VDVR) (Equation 3) for 8 hours (FUNDACENTRO, 2013).

$$aren = are \times \sqrt{\frac{T}{T_0}} \tag{2}$$

Where: *are* is acceleration resulting from exposure, representative of daily occupational exposure, m s^{-2}, *T* is the duration of the daily working day expressed, hours or minutes and *T0* is 8 hours or 480 minutes.

$$VDVR = \left[\sum_{j} (VDV \times exp_j)^4 \right]^{\frac{1}{4}} \tag{3}$$

Where: *VDVexpj* is the exposure vibration dose value representative of the daily occupational exposure on the "*j*" axis, with "*j*" being equal to "x", "y" or "z" (m $s^{-1.75}$).

The results were compared with the exposure limits established by NHO 09 for an 8-hour daily exposure (Table 2).

Table 2. Exposure limits to whole-body vibration according to NHO 09.
Tabela 2. Limites de exposição à vibração de corpo inteiro conforme NHO 09.

aren (m s^{-2})	**VDVR (m $s^{-1,75}$)**	**Technical consideration**	**Recommended performance**
0 to 0.5	0 to 9.1	Acceptable	Acceptable maintenance of existing condition
0.5 to 0.9	9.1 to 16.4	Above the action level	Minimum adoption of preventive measures
0.9 to 1.1	16.4 to 21	Region of uncertainty	Adoption of preventive and corrective measures aimed at reducing the daily dose
Over 1.1	Over 21	Over the exposure limit	Immediate adoption of corrective measures

Subtitle: aren is acceleration resulting from normalized exposure (m s^{-2}); and VDVR is the resulting vibration dose value (m $s^{1,75}$) (Fundacentro, 2013).

Statistical analysis

A completely randomized design was employed using a 4×2 factorial scheme, consisting of four work cycle elements and two work shifts. The machine's operating cycle was considered the experimental unit. The average durations of the partial activities were compared using Tukey's test ($\alpha \leq 0.05$). To compare WBV between day and night shifts, the acceleration resulting from normalized exposure (aren) and the vibration dose value (VDVR) over an 8-hour period were analyzed using Student's t-test ($\alpha \leq 0.05$). Subsequently, WBV-related variables (amj and VDVj) were analyzed by work element using an internally randomized design, with means compared by the Tukey HSD/Kramer test ($\alpha \leq 0.05$).

RESULTS

Time Study

A total of 27 operational cycles were timed during each work shift, with 15 and 6 cycles required, respectively, to reach the permissible error limit of 10%. The average times for the partial activities within the forwarder work cycles showed no statistically significant difference between the day and night shifts (Table 3). The activities decreased in the following order: loading, unloading, empty trip, and loaded trip. As a result, the times spent on individual work elements did not significantly affect the overall cycle times, which ranged from 1,752 seconds for the day shift to 1,783 seconds for the night shift.

Table 3. Average durations of partial activities in the forwarder's work cycle for both day and night shifts.
Tabela 3. Tempos médios das atividades parciais do ciclo de trabalho do forwarder nos turnos diurno e noturno.

Work element	Work Shifts	
	Day	Night
Empty trip (h)	113 d	165 d
Loading (h)	900 b	941 b
Loaded trip (h)	134 d	153 d
Unloading (h)	604 c	524 c
Total time (h)	1,752 a	1,783 a

Subtitle: Averages followed by the same letter do not differ statistically by the Tukey test ($\alpha \leq 0.05$).

On average, operators spent approximately 6.6 hours inside the cabin per workday, with the time allocated to each activity detailed in Table 4.

Table 4. Average durations of partial activities in the forwarder's work cycle during day and night shifts.
Tabela 4. Tempos médios de atividades parciais do ciclo de trabalho do forwarder nos turnos diurno e noturno.

Work element	Work Shifts	
	Day	Night
Empty trip (h)	0.6	0.6
Loading (h)	3.5	3.5
Loaded trip (h)	0.6	0.6
Unloading (h)	1.9	1.9
Total Time (h)	6.6	6.6

Levels of exposure to WBV in work shifts

The average AREN values for the two work shifts showed no statistically significant difference according to the t-test ($p = 0.19$). Interestingly, AREN values were approximately 8% lower during the night shift, contradicting the study's hypothesis, which anticipated higher values at night (Figure 1a).

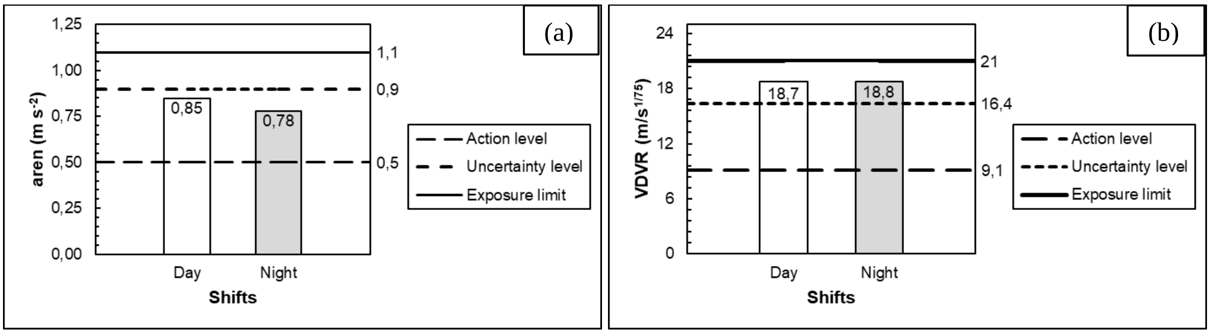

Figure 1. Average AREN values for the two work shifts (a); Average VDVR values for the two work shifts (b).
Figura 1. Valores médios de aren nos dois turnos de trabalho (a); e Valores médios do VDVR nos dois turnos de trabalho (b).

The VDVR values for both work shifts showed no statistically significant difference (p = 0.98) according to the t-test. Although they were below the tolerance limit, they remained above the uncertainty level, indicating the need for preventive measures (Figure 1b).

Levels of exposure to whole-body vibration (WBV) varied across the work elements of the operational cycle.

Regarding the axes of average acceleration, the highest levels were observed on the y-axis, followed by the z-axis (Table 5), primarily during the empty and loaded trips. This suggests greater vibration activity in the driving work elements.

Table 5. Average acceleration in the partial activities of the work cycles during the day and night shifts.
Tabela 5. Aceleração média nas atividades parciais dos ciclos de trabalho nos turnos diurno e noturno.

Work element	Work Shifts					
	Day			Night		
	am_x	am_y	am_z	am_x	am_y	am_z
Empty trip ($m\ s^{-2}$)	0.49 a	0.84 a	0.68 a	0.36 a	0.58 ab	0.54 ab
Loading ($m\ s^{-2}$)	0.23 b	0.37 b	0.32 b	0.21 b	0.39 b	0.35 b
Loaded trip ($m\ s^{-2}$)	0.52 a	0.80 a	0.67 a	0.42 a	0.76 a	0.60 a
Unloading ($m\ s^{-2}$)	0.20 b	0.33 b	0.29 b	0.19 b	0.34 b	0.30 b
Interrup. ($m\ s^{-2}$)	0.05 c	0.07 c	0.08 c	0.04 b	0.07 b	0.04 b

Subtitle: am is mean acceleration. Averages followed by the same letter, in the column, do not differ statistically by the Tukey HSD / Krammer test ($\alpha \leq 0.05$).

The average acceleration values for both empty and loaded trips showed no statistically significant difference, contrary to the expectation that WBV would be lower during the loaded trip. Additionally, WBV levels in both trip types were higher than those observed during the loading and unloading tasks (Table 6).

Table 6. Vibration dose values for the partial activities of the work cycles during the day and night shifts.
Tabela 6. Valor da dose de vibração nas atividades parciais dos ciclos de trabalho nos turnos diurno e noturno.

Work element	Work Shifts					
	Day			Night		
	VDV_x	VDV_y	VDV_z	VDV_x	VDV_y	VDV_z
Empty trip ($m\ s^{-1,75}$)	2.94 a	5.04 a	5.09 a	2.65 a	4.04 ab	5.57 a
Loading ($m\ s^{-1,75}$)	2.32 ab	3.64 bc	3.74 ab	1.82 a	3.00 b	3.47 ab
Loaded trip ($m\ s^{-1,75}$)	2.81 a	4.43 ab	4.92 a	2.58 a	4.67 a	5.15 a
Unloading ($m\ s^{-1,75}$)	1.77 b	2.57 c	2.64 b	1.84 a	3.00 b	3.59 ab
Interrup. ($m\ s^{-1,75}$)	0.26 c	0.38 d	0.49 c	0.35 b	0.63 c	0.39 b

Subtitle: VDVR is the resulting vibration dose value. Averages followed by the same letter, in the column, do not differ statistically by the Tukey HSD / Krammer test ($\alpha \leq 0.05$).

Figure 4 illustrates a typical WBV graph for a portion of the workday during the log extraction activity with the forwarder. As shown, the empty trip was the work element that exhibited the highest acceleration peaks, indicating that driving work elements are more demanding compared to the other tasks.

DISCUSSION

This study found that the highest risk of exposure to whole-body vibration (WBV) occurred when the wheels made contact with the ground during the travel work elements, rather than from impacts caused by the boom and grapple during loading and unloading. The average WBV levels during both day and night shifts were below the exposure limit and uncertainty threshold. No statistical difference was found between the two shifts, although WBV was slightly lower during the night shift. Similar WBV levels were reported by Santos *et al.* (2020). It is worth noting that the machine operated under better conditions during the night shift, with areas marked and signaled for obstacles by the operation supervisor, and the machine was equipped with an efficient lighting system for night work.

Therefore, the need for preventive measures in the log extraction process using a forwarder is evident. It is crucial to carefully plan operations and choose traffic routes that provide optimal conditions for the machine. Additional preventive measures could include regular assessments of WBV exposure, educating workers about the associated risks, ensuring operators can report abnormal WBV levels to supervisors, implementing health surveillance for operators, and adopting alternative work procedures and methods to reduce exposure.

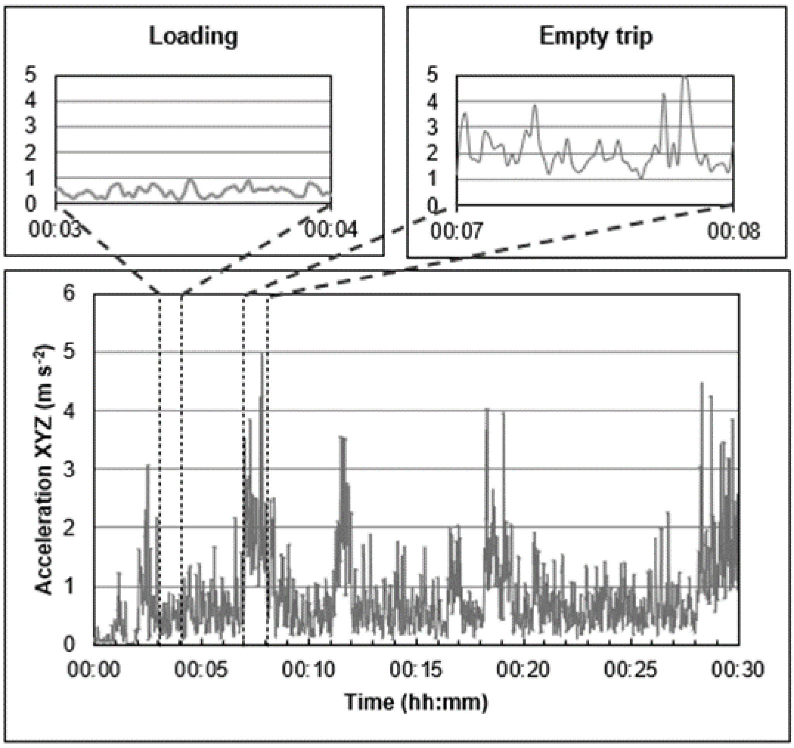

Figure 4. Acceleration graphic indicating that WBV is higher in the work elements in which the forwarder moves through the stand.

Figura 4. Gráfico de aceleração indicando que a VCI é maior nos elementos de trabalho em que o forwarder se movimenta pelo povoamento.

To reduce WBV exposure levels in machine operators, Donati (2002) suggested several alternatives: reducing vibration at the source through proper machine maintenance and careful vehicle selection; incorporating suspension systems, such as tires, vehicle suspensions, suspension cabins, and seats; and improving the ergonomic design of the cabin to promote proper working postures. Other measures include increasing the thickness of the seat foam and ensuring regular maintenance, as machines experience high usage and continuous work shifts, leading to rapid deterioration (LEWARK, 2005).

The results of this study align with findings from other authors (JANKOVSKÝ *et al.*, 2016; MARZANO *et al.*, 2017), who, when evaluating different forwarder models, reported WBV levels below the tolerance limit but above the action level, recommending preventive measures such as modifying the machine's suspension. According to Rehn *et al.* (2005), terrain characteristics significantly impact WBV exposure levels during forwarder operations, particularly during driving activities. However, both loading and unloading also exhibit high vibration levels. Häggström *et al.* (2016) argued that this vibration magnitude can be reduced by adjusting the driving method and vehicle operating speed, as well as through operation planning that takes terrain conditions and wood harvest residue presence into account.

The results of this study also show similarities compared to Tiemessen *et al.* (2007). Both confirm significant exposure to whole-body vibration (WBV) and its health risks. The main similarity is the identification of machine displacement as the most critical phase for exposure, whereas the difference lies in the focus: Tiemessen *et al.* discuss preventive strategies, while this study quantifies vibration under different operational conditions.

We observed higher acceleration levels on the y-axis, particularly during the empty and loaded trips, which is consistent with findings from other authors such as Rehn *et al.* (2004) and Poje *et al.* (2020). This could be attributed to the lateral displacement of the machine's wheels during these work elements, caused by the presence of residues on the traffic path. Reducing such residues is recommended to minimize environmental impacts caused by machine traffic (SZYMCZAK *et al.*, 2014). Additionally, the high average acceleration levels on the z-axis could be a result of the "bumps" encountered when traveling over rough terrain and obstacles, such as stumps left from felled trees.

The results of this study partially corroborate the findings of Butkus *et al.* (2020), who also identified that the loaded transport and empty return phases are the most critical in terms of whole-body vibration (WBV) exposure. However, while the present study focused on evaluating WBV levels in forwarders operating in different shifts, Butkus *et al.* (2020) analyzed the impact of using tracks on wheels to reduce vibration. They observed that forwarders equipped with tracks exhibited significantly lower WBV exposure compared to wheeled-only models, especially during loaded and unloaded travel operations. Additionally, Butkus *et al.* (2020) highlighted that operating speed directly influences WBV levels, with increases in speed leading to significant rises in vibration acceleration. This variable was not explored in the present study but could represent a complementary approach for future research.

The average acceleration values during empty and loaded trips did not show a statistically significant difference between them, which contradicted the expectation that WBV would be lower in the loaded trip. However, the levels of WBV in both the empty and loaded trips were higher compared to the loading and unloading work elements. Therefore, it is essential to plan the operation carefully, considering the irregularities in the terrain, the presence of rocks and residues from wood harvest, and implementing more stringent quality control of stump heights. Several studies (FIEDLER *et al.*, 2013; NADOLNY *et al.*, 2019) have reported the presence of stumps greater than 10 cm, which exceeds the height limit for the harvester head configuration.

To reduce whole-body vibration (WBV) exposure in forwarder operators during eucalyptus harvesting, several practical recommendations can be made. These include adjusting the operating speed, particularly during empty and loaded trips, optimizing tire characteristics and inflation pressure, managing stump height and wood residue disposal, and providing continuous training for operators on safe practices and driving techniques. Additionally, implementing regular breaks during work shifts can help minimize the effects of vibration and enhance worker comfort and health.

For future research, it is recommended to further investigate the effects of wheel characteristics and tire inflation on whole-body vibration levels, as these factors can significantly influence operator exposure. Additionally, studies on machine operating speed, stump height quality control, and the disposal location of logging residues may provide valuable insights into reducing vibration exposure. It would also be interesting to assess how different soil conditions and variations in forest types influence vibration intensity, considering that these factors may modify machine behavior during operations. Lastly, more research is needed to evaluate the long-term effects of continuous vibration exposure on forwarder operators, particularly regarding occupational health.

CONCLUSIONS

- Occupational exposure to whole-body vibration (WBV) in forwarder operators was below emergency limits, but the vibration levels still require the implementation of preventive measures to avoid long-term increases and protect workers' health.
- The most harmful work elements in the forwarder operational cycle, in terms of WBV exposure, were the empty and loaded trips, where vibration was more intense due to the vehicle's movement across the stand. On the other hand, the loading and unloading activities showed lower vibration levels, suggesting that mitigation strategies should be applied especially during the vehicle movement phases.
- The study also highlighted the need for further research on factors influencing WBV levels, such as wheel characteristics, tire inflation, machine operating speed, stump height control, and the location of wood harvest residues, as these aspects may have a direct impact on exposure and operator health.

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