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INFLUENCE OF THE HARVESTER OPERATION MODE ON ERGONOMIC PARAMETERS OF OPERATORS

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Resumo

Influência do modo de operação de harvester sobre parâmetros ergonômicos dos operadores. Alterações no modo de operação de máquinas florestais provoca a redução do consumo de combustível, contudo pode afetar fatores ergonômicos dos operadores. Dessa forma, objetivou-se com a presente pesquisa avaliar parâmetros ergonômicos da operação com harvester em distintos modos de operação. Os modos de operação foram obtidos por meio da alteração da rotação do motor e vazão da bomba hidráulica. A máquina foi programada para operar com nas rotações do motor de 2.060; 2.000; 1.950; e 1.900 rpm e vazão da bomba hidráulica de 300; 295; 290 l min^{-1}, totalizando 12 modos de operação. A pesquisa foi realizada nos volumes médios das árvores de 0,08; 0,12; e 0,16 m³ árvore^{-1}. Foram mensurados os valores de Aceleração resultante de exposição normalizada (Aren) e o índice TOR (Taxa de Ocupação Real) – TOMCAR (Taxa de Ocupação Máxima Considerando Atividades Repetitivas). Os dados foram submetidos a análise de variância e quando significativos comparados pelo teste de Tukey. Alterações no modo de operação da máquina provoca decréscimos significativos nos valores de Aren. A execução da operação deslocamento e busca expõem os operadores aos maiores valores de aceleração resultante de exposição normalizada. A operação com harvester se caracteriza como causadora de doenças ocupacionais.

Palavras-chave: Aceleração resultante; Índice TOR-TOM, Colheita florestal

Abstract

Changes in the way of operating forest machines causes a reduction in fuel consumption, however it can affect ergonomic factors of the operators. Thus, the objective of this research was to evaluate ergonomic parameters of the operation with harvester in different modes of operation. The operating modes were obtained by changing the engine speed and flow rate of the hydraulic pump. The machine was programmed to operate at engine speeds of 2,060; 2,000; 1,950; and 1,900 rpm and hydraulic pump flow of 300; 295; 290 l min^{-1}, totaling 12 operating modes. The research was carried out on the average tree volumes of 0.08; 0.12; and 0.16 m³ tree^{-1}. The Acceleration values resulting from normalized exposure (Aren) and the TOR (Real Occupancy Rate) - TOMCAR (Maximum Occupancy Rate considering Repetitive Activities) were measured. The data were submitted to analysis of variance and when significant compared by the Tukey test. Changes in the machine's operating mode cause significant decreases in Aren values. A execução da operação deslocamento e busca expõem os operadores aos maiores valores de aceleração resultante de exposição normalizada. A operação com harvester se caracteriza como causadora de doenças ocupacionais. The execution of the displacement and search operation exposes operators to the highest values of acceleration resulting from normalized exposure. The operation with harvester is characterized as causing occupational diseases.

Keywords: Resulting acceleration, TOR-TOM index, forest harvest.

INTRODUCTION

The harvester is a self-propelled forestry tractor, designed to perform all the operations that make up the forestry cut, such as felling, delimbing, debarking, tracing and stacking the wood. The operation with a harvester is complex, as it is influenced by social, environmental, forestry and mechanical factors. However, these machines made it possible for large areas to be harvested in a short space of time and thus provided that the growing demand for wood in the market was met.

Despite the series of advantages that the harvester provides for forest harvesting operations, it has a high operating cost (SANTOS *et al.*, 2017). As a result, in recent years, large forestry companies have reduced the engine speed and hydraulic pump flow rate. This measure aims to provide a reduction in the hourly fuel consumption of the machine and consequently significant gains in the final cost of wood.

According to Prinz *et al.* (2018) the harvester's work settings affect fuel consumption, with the best results being obtained in the operating modes that have the lowest engine speed regime. According to Santos *et al.* (2018) reducing harvester engine speed causes significant decreases in hourly fuel consumption. In the research developed by Spinelli *et al.* (2018) it was found that simply adjusting the engine rpm reduces fuel consumption and does not affect the productivity of wood chippers.

However, changes in engine speed and hydraulic pump flow can positively or negatively affect the ergonomics of forest machine operators, since all machine commands are activated by buttons and joysticks. Research has found that wood harvesting operations are arduous and uncomfortable, as they are carried out in the same posture (sitting), transmit vibration to operators during 75% of the workday, and present cognitive and motor demands, with high levels of repeatability (GERASIMOV & SOKOLOV, 2014; ALMEIDA *et al.*, 2015). According to Caffaro *et al*. (2016) forest machine operators need solutions that provide the reduction of whole-body vibration values.

Based on the above, the objective of this research was to evaluate ergonomic parameters of harvester operation in different operating modes.

MATERIAL AND METHODS

Characterization of the study area

The research was carried out in areas of forest harvesting operations located in the extreme south of the state of Bahia. The region has an average annual temperature of 24.4 °C and an average annual rainfall of 1,350 mm. The areas where the experimental plots were allocated had a flat relief, populated with hybrid clones of Eucalyptus grandis x Eucalyptus urophylla, planted at a spacing of 4 meters between rows and 2.5 meters between plants. Data collection was performed during the day, starting at 6:00 am and ending at 3:00 pm. The tests were conducted in the absence of rain.

Harvest system

The research was carried out in a forest harvesting system for short logs (cut to length) composed of harvester and forwarder machines.

The harvester was responsible for cutting and processing the trees, leaving bundles on the ground surface with 6.20 meter long logs. The machine was simultaneously felling four rows of trees. The extraction of wood from the interior of the stands to the edges of the roads was carried out by the forwarder. The machine entered the reverse stand and carried out the loading of the bundles present on both sides of the branch.

Used machine

The harvester used was a combination of a Komatsu hydraulic excavator, model PC200F-8M0, and a Komatsu head, model 370E. The PC200F-8M0 was a tracked machine, equipped with the 6-cylinder Komatsu SAA6D107E-1 diesel engine and rated 110 kW at 2,000 rpm. The machine's hydraulic system was a Hydraumind type, consisting of two Komatsu hydraulic pumps, HPV95+95 model, both with variable displacement pistons and a maximum flow rate of 219 liters per minute for each pump.

Determining the individual volume of trees

The individual volume of the trees (VMI) was determined using the diameter and length sensors on the machine head. Subsequently, the VMI was calculated by the MaxiXplorer operating system. The length sensor was positioned on the head feed rollers. The value was measured based on the circumference and rotation of the rolls. The diameter sensor was positioned on the delimbing knives of the head, and the diameter was measured according to the inclination angle of the knives.

Selection of engine speed and hydraulic pump flow

The harvester was programmed to operate in twelve operating modes, resulting from the combination of engine speed and hydraulic pump flow (Table 1). Engine speeds of 2060 were selected; 2,000; 1,950 and 1,900 rpm and hydraulic pump flow of 300; 295 and 290 l min^{-1}, totaling twelve operating modes. The operating modes were determined from the nominal engine speed and from a preliminary study, where it was evident that it was not feasible to operate machines with engine speed below 1850 rpm and hydraulic pump flow below 285 l min^{-1}. Engine speed and hydraulic pump flow were controlled and selected in the MaxiXplorer machine's Control and Information System.

Table 1. Modes of operation of the harvester.
Tabela 1. Modos de operação do harvester.

Operation mode	Engine RPM (rpm)	Hydraulic pump flow (l min^{-1})
1	2060	300
2	2060	295
3	2060	290
4	2000	300
5	2000	295
6	2000	290
7	1950	300
8	1950	295
9	1950	290
10	1900	300
11	1900	295
12	1900	290

Experimental units

The experimental plots had a rectangular shape, with 100 trees each and an area equal to 720 m². The plots were allocated in areas with flat relief and without the occurrence of planting failures and dead and bifurcated trees. For each operating mode, in each volume, 10 experimental plots were demarcated.

Whole body vibration reviews

Whole body vibration values were measured according to the technical recommendations established by the Occupational Hygiene Standard 09 (FUNDACENTRO, 2013) and by the European Community Directive 2002/44/EC. Measurements of vibration levels were performed with a triaxial accelerometer, brand 01dB, model Vib 008. The device was fixed to the operator's seat and positioned according to the three directions of the orthogonal coordinate system (x, y and z). The values of acceleration resulting from normalized exposure (Aren) were measured in the twelve operating modes of the harvester and in each operation that make up the operating cycle of the machine.

To account for the acceleration values per operation, the harvester's operational cycle was divided into displacement and search, felling, cutting and processing operations. A video system was installed in the machine's cabin, in order to visualize each operation of the machine's operating cycle cycle and the respective Aren value. The video system time was adjusted in relation to the accelerometer time. Data were processed using the dBMaestro 5.5 software.

TOR Index (Actual Occupancy Rate) - TOMCAR (Maximum Occupancy Rate Considering Repetitive Activities)

The potential of harvester operations to cause disturbances such as fatigue, discomfort, difficulties and injuries was quantified using the TOR (Real Occupancy Rate) - TOMCAR (Maximum Occupancy Rate Considering Repetitive Activities) index, according to the methodology proposed by Couto (2012). The TOR was calculated using the Equation below.

$$TOR = 100\% - PPR - PABE - PPIH - PPC$$

where: TOR = actual occupancy rate (%); PPR = Percentage of rest due to regular breaks (%); PABE = Percentage of time with low-demand activities (%); PPIH = Percentage of habitual irregular pauses (%); PPC = Percentage of very short breaks (%).

To determine the PPR, the time spent with bathroom breaks and labor gymnastics was quantified. Regarding the PABE, the time spent inspecting the machine at the beginning of the workday, changing cutting and cleaning material and organizing the machine at the end of the workday was measured. To account for the time spent with very short breaks during the execution of the work, a video system was installed in the operator's cabin. The video system consisted of four video cameras, a seven-inch monitor and a Mobile Digital Video Recorder (MVDR). One camera was directed towards the left joystick, another towards the direct joystick, one towards the operator's head and the last towards the front of the machine in order to visualize the operation that the machine was performing. Videos of one hundred harvester operating cycles were recorded. Subsequently, it was analyzed whether there were very short pauses between cycles or within the cycle. Only very short pauses were considered, intervals of at least three seconds.

The Maximum Occupancy Rate Considering Repetitive Activities was calculated according to the Equation below.

$$TOMCAR = 95\% - FR - FF - FEE$$

where: TOMCAR = Maximum Occupancy Rate Considering Repetitive Activities (%); FR = Repeatability Factor (%); FF= Strength Factor (%); and FEE = Static Effort Factor (%).

The Repeatability, Force and Static Effort factors were determined according to flowcharts and tables established by Couto (2012). To facilitate the study of repeatability, the components and the respective functions activated by the harvester operators were identified.

At the beginning, middle and end of the workday, operators were submitted to answer a bipolar questionnaire, in order to identify the occurrence or absence of fatigue caused by the operation. The questionnaire was prepared in accordance with Couto (2012).

Data analysis

The data obtained were analyzed by means of Analysis of Variance and when significant compared by Tukey's test at the level of 5% of probability. Aren's data, in each mode of operation, were arranged in a completely randomized design (CRD), with twelve treatments. Aren's data per operation were analyzed considering a 3x3 factorial scheme in CRD, with three volumes of trees and three operations of the operational cycle.

RESULTS

Some operating modes had a significant effect on the Aren values in the three volumes studied (Table 2). The statistically higher values, 0.455; 0.585; and 0.683 m s^{-2}, in 0.08 volumes; 0.12; and 16 m³ $tree^{-1}$, respectively, were observed in operating mode 1. On the other hand, the statistically lower values, 0.375; 0.482; 0.538 m s^{-2} in 0.08 volumes; 0.12; and 16 m³ $tree^{-1}$, respectively, were obtained in operating mode 12. Such results demonstrate a reduction in Aren values of 21.33; 21.37; and 26.95% in 0.08 volumes; 0.12; and 16 m³ $tree^{-1}$, respectively. In all scenarios studied, Aren's values did not exceed the limit value for the 8-hour workday (NHO 09). However, in operating modes 1 to 9 at 0.12 m³ $tree^{-1}$ volume and in all operating modes at 0.16 m³ $tree^{-1}$ volume, it is necessary to adopt preventive measures. According to the guide chart with health precaution zones of the ISO 2631-1:1997 standard (ISO, 1997), Aren values above 0.50 m s^{-2} present potential health risks.

Table 2. Acceleration values resulting from normalized exposure, m s^{-2}, in operating modes.
Tabela 2. Valores de Aceleração resultante de exposição normalizada, m s^{-2}, nos modos de operação.

Operation mode	Engine RPM (rpm)	Hydraulic pump flow (l min^{-1})	Volume (m³ $tree^{-1}$)		
			0.08	0.12A	0.16
	2060	300	0.455A	0.585A	0.683A
2	2060	295	0.455A	0.587A	0.690A
3	2060	290	0.440AB	0.570AB	0.648AB
4	2000	300	0.432ABC	0.548ABC	0.640ABC
5	2000	295	0.417BCD	0.546BC	0.630ABC
6	2000	290	0.423ABC	0.542BC	0.618BC
7	1950	300	0.408ABCDE	0.517CD	0.586CD
8	1950	295	0.390CDE	0.514CD	0.583CD
9	1950	290	0.398BCDE	0.502CD	0.563D
10	1900	300	0.382CDE	0.490D	0.558D
11	1900	295	0.380DE	0.491D	0.548D
12	1900	290	0.375E	0.482D	0.538D

Means followed by the same letter in the columns do not differ from each other by Tukey's test at the 95% probability level.

The type of operation of the harvester's operational cycle and the volume of wood significantly influenced the Aren values (Table 3). The displacement and search operation presented the highest values, followed by wood processing and felling cutting. Statistically higher values of Aren were also observed, 0.607 m s^{-2}, in the volume of 0.16 m³ per tree. This value is 47% higher than that observed in the volume of 0.08 m³ per tree.

Table 3. Aren values (m s^{-2}) per operation and total value per volume studied.
Tabela 3. Valores de Aren (m s^{-2}) por operação e valor total por volume estudado.

VMI (m³ tree^{-1})	Displacement and search	Felling cut	Processing	Total
0.08	0.65 ABa	0.19 Bb	0.22 Bb	0.413C
0.12	0.72 Aa	0.21 Bc	0.33 Ab	0.537B
0.16	0.55 Ba	0.28 Ac	0.35 Ab	0.607A

Means followed by the same letter, lowercase in rows and uppercase in columns, do not differ from each other by Tukey's test at the 5% probability level.

Forest harvesting operations were carried out in a system of shifts and in two shifts, in which operators worked for four consecutive days on the same shift and took two days off. Table 4 shows the actions performed by the operator, the respective ergonomic requirements and the affected body members during wood cutting and processing. It was evident that the harvester operator's activity requires a high level of concentration and requires fast, different and repetitive movements of different body members, regardless of the levels of the factors studied.

Table 4. Technical actions performed during the machine’s operational cycle and the affected body members.
Tabela 4. Ações técnicas executadas durante o ciclo operacional da máquina e os respectivos membros do corpo afetados.

Sequence of operation	**Ergonomic requirements**	**Partes do corpo**
Machine movement	- Stopped sitting; -Need for visualization; and - Command activation.	- Leg muscles; -Left wrist with ulnar deviation; -Hands; -Fingers; -Neck in constant movement; Eyes; and -Shoulder.
Boom drive	-Stopped sitting; -Need for visualization; and - Command activation.	- Right wrist with ulnar deviation; -Eyes; -Hands; -Fingers; and -Shoulder.
Head components drive	-Stopped sitting; -Need for visualization; and - Command activation.	--Eyes; -Hands; and - Fingers.

In Table 5 it is possible to observe the results obtained with the calculation of the Real Occupancy Rate (TOR) and Maximum Occupancy Rate Considering Repetitive Activities (TOMCAR). There were no significant differences between the values of the three volumes studied and between the modes of operation. During the execution of the research, Habitual Irregular Pauses, Very Short Pauses and Force Factor were not observed. As TOMCAR presented values lower than TOR, in all scenarios studied, the operation with a harvester is characterized as an ergonomic risk, requiring the adoption of mitigating measures and monitoring of workers, regardless of the mode of operation and volume of wood.

Table 5. Actual Occupancy Rate (TOR) and Maximum Occupancy Rate considering Repetitive Activities (TOMCAR) in all volumes surveyed.
Tabela 5. Taxa de Ocupação Real (TOR) e Taxa de Ocupação Máxima Considerando Atividades Repetitivas (TOMCAR) em todos os volumes pesquisados.

Type of break	VMI (m^3 tree^{-1})		
	0,08	0,12	0,16
PPR (%)	7,50	6,88	7,50
PABE (%)	8,75	8,54	8,96
PPIH (%)	0,00	0,00	0,00
PPC (%)	0,00	0,00	0,00
Regulation mechanism (%)	5,00	5,00	5,00
TOR (%)	78,75	79,58	78,54
FR (%)	3,00	3,00	3,00
FF (%)	0,00	0,00	0,00
FEE (%)	24,00	24,00	24,00
TOMCAR (%)	68,00	68,00	71,00

Where: PPR = Percentage of rest due to regular breaks (%); PABE = Percentage of time with low-demand activities (%); PPIH = Percentage of habitual irregular pauses (%); PPC = Percentage of very short breaks (%); FR = repeatability factor; FF = force factor; and FEE = static effort factor.

Na Tabela 6 é possível observar o número de vezes que operador acionava os componentes da máquina durante a jornada de trabalho. Observou-se que no volume de 0,08 m^3 árvore^{-1} os operadores executaram maior quantidade de movimentos repetitivos e que no modo de operação 12 houve redução no número de movimentos. Em todos os cenários analisados o componente mais acionado foi o joystick esquerdo, seguido do botão 2 do joystick direito e o joystick direito.

Table 6. Number of times per shift that the operator triggered machine commands.
Tabela 6. Número de vezes, por turno, que o operador acionava os comandos da máquina

VMI	Operation mode	A	B	C	D	E	F	G	H	I
0.08	1	1100	3336	1760	2200	1027	843	697	1100	201
	2	1114	3379	1782	2228	1040	854	706	1114	204
	3	1055	3202	1689	2111	985	809	668	1055	193
	4	1078	3269	1724	2156	1006	826	683	1078	197
	5	1105	3352	1768	2210	1031	847	700	1105	202
	6	1055	3201	1689	2111	985	809	668	1055	193
	7	1065	3232	1705	2131	994	817	675	1065	195
	8	1016	3081	1625	2031	948	779	643	1016	186
	9	990	3002	1583	1979	924	759	627	990	181
	10	1070	3246	1712	2140	999	820	678	1070	196
	11	1017	3084	1627	2034	949	780	644	1017	186
	12	996	3020	1593	1991	929	763	631	996	182

0.12	1	752	2871	1465	1505	891	673	871	832	141
	2	751	2867	1463	1503	890	672	870	830	141
	3	726	2769	1413	1452	859	649	840	802	136
	4	747	2851	1455	1494	885	668	865	826	140
	5	759	2896	1478	1518	899	679	879	839	142
	6	720	2746	1401	1439	852	644	833	795	135
	7	719	2745	1401	1439	852	644	833	795	135
	8	691	2635	1345	1381	818	618	800	763	129
	9	658	2512	1282	1317	780	589	762	728	123
	10	678	2587	1320	1356	803	607	785	749	127
	11	707	2696	1376	1413	837	632	818	781	132
	12	665	2537	1295	1330	787	595	770	735	125
0.16	1	848	3228	1368	1696	1204	903	903	1067	159
	2	823	3131	1327	1645	1167	876	876	1035	154
	3	801	3047	1291	1601	1136	852	852	1007	150
	4	853	3249	1377	1707	1211	909	909	1074	160
	5	821	3127	1325	1643	1166	874	874	1033	154
	6	772	2939	1245	1544	1096	822	822	971	145
	7	846	3222	1365	1693	1201	901	901	1065	159
	8	790	3007	1274	1580	1121	841	841	994	148
	9	752	2861	1212	1503	1067	800	800	945	141
	10	808	3077	1304	1617	1147	860	860	1017	152
	11	769	2927	1240	1538	1092	819	819	968	144
	12	734	2794	1184	1468	1042	781	781	923	138

Where: VMI = individual average volume (m³ tree-1); A = number of cycles; B = left joystick; C = right joystick; D = right joystick button 2; E = left joystick button 2; F = left joystick button 4; G = left joystick button 1; H = left joystick button 3; and I = exchange 1 and 2.

DISCUSSION

The increase in Aren values in operating modes 1 to 9 was due to the increase in the engine speed regime and hydraulic pump flow. The increase in engine speed causes an increase in the upward and downward movement of the pistons and a consequent increase in the machine's displacement speed. It should be noted that between the engine and the chassis of the machine there is no mechanism to dampen vibrations, which facilitates the transmission of vibrations to the operator. Similar results were found by Santos *et al.* (2020).

Marzano *et al.*, (2017) evaluated the acceleration values resulting from normalized exposure of different harvester models, and determined a value of 0.37 m s^{-2}. On the other hand, Sherwin *et al.*, (2004) determined the acceleration values between 0.277 and 0.527 m s^{-2}, for a harvester operating with different tire inflation pressures. The results cited are similar to those observed in the present research when the harvester was operating in the forest stand with an average volume of 0.08 m³ $tree^{-1}$. It should be noted that exposure to whole-body vibration amplitudes can cause musculoskeletal disorders in forest machine operators (OSBORNE *et al.*, 2012).

The highest values of Aren in the displacement and search operation occur because during the operation the machine translates over the uneven surface of the soil, with the presence of stumps and stones, which results in higher vibration values. The increase in Aren values in the processing and felling operations, with the increase in the volume of trees, occurred because the logs with greater weight have greater inertia, greater impact on the ground during felling and greater impact of feed rollers and knives. delimbing and peeling. However, it is worth noting that the statistical difference between the Aren values of the displacement and search operation, between the volumes of wood, occurred due to the operational conditions of the soil and not necessarily due to the volume of the wood, since during the execution of the operation the machine did not come into contact with the logs.

As TOMCAR presented values lower than TOR, it is necessary to adopt mitigating measures, such as increasing breaks during the workday or reducing the number of hours of the workday. According to Couto (2002), the operation with a harvester requires repetitive movements, static postures and psychic capacity of the workers, therefore, breaks are important and indispensable mechanisms to balance the biomechanics of the organism, compensating the work overload. According to Gerasimov and Sokolov (2014), forest machine operators are being affected by injuries to the neck, arms and cervical spine, caused by excessive intensity at work, staying too long in ergonomically incorrect fixed positions and by repetitive short-cycle movements.

From the Bipolar questionnaire, it was found that the modes of operation 9; 11; and 12 intensified the symptoms of fatigue, physical and mental tiredness, compromised productivity and pain in the arm, wrist and hands on the left and right sides. Such symptoms were more expressive in the volume of 0.16 m^3 $tree^{-1}$. According to the operators, in these combinations, the activities performed by the machine were slow, thus making the operation monotonous and heavier, requiring greater physical and mental effort to keep the machine's productivity high. One of the workers reported the following: *"(...) when the engine speed and pump flow are very low, I have to work for the machine, and not the other way around, which would mean the machine would work for me".*

When the machine was programmed to operate in operating mode 9; 11; and 12, operators performed fewer movements, due to the decrease in operating income. The greater amount of repetitive movements performed in the volume of 0.08 m^3 per tree, occurred due to the need to fell a greater number of trees to meet the goal established by the company. The left joystick was the most used component, mainly in the VMI of 0.08 m^3 $tree^{-1}$. This component was used to drive the secondary hydraulic cylinder of the boom, which provided its extension or retraction. According to Østensvik *et al.* (2008) repetitive wrist movements can cause several injuries in the region, such as Carpal Tunnel Syndrome, Rotator Cuff Syndrome and Tendinitis. In addition to these wrist diseases, according to the same authors, harvester operation causes neck pain for operators.

CONCLUSION

- Reductions in engine speed, hydraulic pump flow and average wood volume cause a reduction in Acceleration values resulting from normalized exposure that harvester operators are exposed to. The pan and seek operation exposes the operator to the highest levels of Acceleration resulting from normalized exposure.
- Operation with harvester is characterized as a cause of occupational diseases, and the modes of operation 9; 11; and 12 intensify the symptoms of fatigue, physical and mental tiredness, compromised productivity and pain in the arm, wrist and hands on the left and right sides.

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