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Vibration levels and daily vibration exposure while using different tools in a forest cleaning

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Abstract

Forest cleaning, being an operation that requires investment, but the return on investment is due for the next generations, utilizes tools and methods that mostly haven't been humanized. Harmful vibration is still present in today's forestry operations, and new tools provide possible reduction of exposure to vibrations. Petrol chainsaw and battery chainsaw (late cleaning) and billhook, machete, and battery shears (early cleaning) were used and observed in this study. Vibration levels were measured and assessed using validated Brüel & Kjær 4447 vibrometer which complies with the ISO 8041:2017 standard. The measurement was performed according to the recommendations of ISO 5349-1:2001 and ISO 5349-2:2001 standards. Vibration exposure was assesed using work sampling method on the obtained video recordings in order to calculate relative shares of different work elements. Results show that hand tools (machete and billhook) are causing the highest vibration levels, while battery shears cause the lowest. Battery chainsaw causes higher vibration levels while cutting, but lower daily vibration exposure than petrol chainsaw. A detailed revision in the classification of tools is needed, considering their ability to produce and transmit harmful vibrations to the operator. Using the current classification, the daily exposure to vibration of workers in early forest cleaning is high above legislative values.

Key words: forest cleaning; hand tools; battery tools; vibration levels; vibration exposure

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1. Introduction

Forest cleaning is one of the work processes of forest tending that is carried out in the developmental stages of saplings and young trees, this work process removes from the stand everything that is considered poor quality and superfluous for the stand future development such as cancer, bent, forked, broken, branched, damaged trees, trees with abnormally developed canopy, trees with broken, damaged or deformed top, shoots, overgrowth, trees deformed in the various shapes, etc., therefore forest cleaning has the character of negative selection (Anić 2007).

Forest cleaning is done in the early years after felling or artificial rejuvenation to eliminate competitive vegetation that outgrows the young or planted trees (Thompson & Pitt 2003). The rapid growth of stronger breeding species after harvest requires an early cleaning procedure in artificially or naturally rejuvenated stands to ensure optimal sapling growth (Jobidon et al. 2003; Thompson & Pitt 2003). Cleaning regulates the stand shape by influencing the type, shape, and ratio of the mixture, parameters that are very important for the future structure of the stand (Anić 2007).

Forest cleaning requires financial investment, and the results of work in the form of a quality stand will only be exploited by future generations. Therefore, since this is a silvicultural procedure that does not bring direct financial income, the improvement of these operations was not a priority, and the methods and tools used in these works are outdated (Bačić et al. 2019). Furthermore, some studies state that, unlike wood harvesting operations which are highly mechanized and use efficient mechanization and equipment, silvicultural operations, especially forest cleaning, are performed by manual or motor-manual methods involving a high proportion of manual labor (de Oliveira et al. 2014). In Croatian forestry, sickles, machetes, and billhooks are used in early forest cleaning, and so-called “silvicultural” chainsaws are used in late forest cleaning where hand tools are not an apropriate tool.

Mechanical forest cleaning can generally be divided into two parts according to the diameter of the trees and the tools used: manual cleaning (early forest cleaning)

**Corresponding author. Zdravko Pandur, e-mail: zpandur@sumfak.unizg.hr* and motor-manual cleaning (late forest cleaning). During manual cleaning, the worker holds a one-handed billhook or machete in one hand, and with the other hand bends a tree that will be cut down for easier cutting. Two-handed billhooks are more common due to the longer range and stronger cutting force. In that case, the worker can use a two-handed billhook either with one or both hands. Sometimes more swings are needed to perform in order to cut. After cutting, the worker lowers the cut tree from the canopy zone and lays it on the ground. The distribution of felled trees is not uniform, trees located on the edge of the silvicultural trails are placed on those trails however, felled trees within the cleaned area (bounded by silvicultural trails and haulage tracks) are distributed according to the further needs of workers. Sometimes most of the felled trees are disposed of in a forest gap to give the worker more freedom of movement and access to other trees.

In the operations of cleaning even-aged stands in which hand tools can no longer be used, a professional chainsaw of smaller dimensions and smaller mass is mainly used. In such stands, some trees that can be characterized as overgrown reach over 20 cm in diameter on the stump, so the use of a chainsaw in such cleaning work is necessary. Usually, the first cut is at an angle and at the height of the worker's shoulder, so that the upper part of the tree can "slip" from the lower part. Then, if necessary, the worker makes one or two more cuts in the same way until the canopy is lowered to the ground. The worker then makes another horizontal cut in the stump of the remaining part of the tree.

Since the introduction of chainsaws in forestry, numerous studies have reported signs and symptoms associated with vibration exposure while working with a chainsaw in forestry (Miura et al. 1965; Axelsson 1968; Barnes et al. 1969; Taylor et al. 1971). There are many synonyms for diseases caused by vibrations, the most common is the so-called "White finger disease" or secondary Raynaud's syndrome (Tambić Bukovac & Šenjug Perica 2017). Numbness in the hands and arms, tingling in the fingers, and deterioration of tactile perception have been detected in workers who have been exposed to hand-arm vibrations (Seppäläinen 1972; Araki et al. 1976; Brammer & Pyykkö 1987). Hand-arm vibrations cause disorders in the blood supply to the fingers and in the peripheral nerves of the hands and arms (Neri et al. 2018). Workers exposed daily to excessive vibrations transmitted to the hand-arm system could suffer, on long term, blood flow disorders in fingers and disorders of neurological functions and movements of hand and arm (Forouharmajd et al. 2017).

The daily vibration exposure values for the hand-arm system specified by EU Directive 2002/44/EC (2002) are prescribed as a daily exposure action value of 2.5 m/s^2, and a daily exposure limit value of 5 m/s^2. Once the exposure action value is exceeded, the employer shall establish and implement a program of technical and organizational measures intended to reduce to minimum exposure to mechanical vibration. Should workers be exposed above the exposure limit value, the employer shall take immediate action to reduce exposure below the exposure limit value. Due to the aforementioned harmful effects of vibrations, the working hours of workers on chainsaws are regulated in the Republic of Croatia, more precisely according to the Ordinance on Occupational Safety and Health in Forestry (1986), a worker may not work effectively with a chainsaw for more than four hours a day.

There are many influencing factors on which the level, transmission, and exposure to vibration depend. According to ISO 5349-1:2001 (2001), the risk of consequences depends on the level of vibration, duration of exposure, and frequency. Lower saw mass causes higher measured vibration levels (Malchaire 2020). Increasing the stiffness of the spring increases the natural frequency of the system, while increasing the mass reduces the natural frequency of the system (Bower et al. 2022). The grip strength of a chainsaw handle, which affects the transmission of vibrations to the hand-arm system, depends on the worker's work experience, work operation, and hardwood. Taking this into account, the grip is stronger in less-experienced workers, in felling and sawing, and in the wood of higher hardness (Malinowska-Borowska et al. 2011; Malinowska-Borowska et al. 2012; Malinowska-Borowska & Zieliński 2013). According to ISO 11681-1:2011 (2011), the main factors affecting the level of vibration in chainsaws are mainly dynamic forces in the motor, cutting mode, unbalanced moving parts, impacts in gears, bearings, and other mechanisms, and also the interaction between worker, chainsaw, and wood being cut. Although chainsaw parts degrade with years of use, Landekić et al. (2020) concluded that age, i.e. years of use does not affect the level of vibration in used petrol chainsaws. Studies (Colantoni et al. 2016; Neri et al. 2018; Poje et al. 2018; Huber et al. 2021) indicate significantly lower noise and vibration levels in battery chainsaws compared to petrol chainsaws of the same class. Goglia et al. (2011, 2012) in their study of the work with chainsaw silvicultural operations record the daily exposure of workers to vibrations above the warning limit and in some cases 4.3 m/s^2 and 4.5 m/s^2.

In addition to chainsaws that are used in motor-manual cleaning, and are a well-known and researched source of vibration, tools used in manual cleaning methods (billhook and machete) can also have a negative impact on worker health. The level of vibration is significantly affected by the type of handle with which the tool is equipped. Hardwood handles (ash, hickory, and oak) with a straight wire that is parallel to the tool blade transmit less vibration to the hands of workers than fiberglass and other synthetic handles (Beckley 2019). Kocjančić (2018) states the length of the handle and the material as the main factors in the transmission of vibrations on chopping axes. As an alternative to the manual method of forest cleaning using hand tools, intensive research on the use of battery shears is being conducted in Croatian forestry (Bačić et al. 2019). Bačić et al. (2020) report significantly higher levels of daily exposure to vibration A(8) when working with a one-handed billhook than when working with a chainsaw.

Therefore, the aim of this paper is to evaluate and compare new battery tools and conventional tools used in forest cleaning from an vibration exposure standpoint.

2. Materials and methods

2.1. Observed tools and workers

In the early cleaning, Stihl ASA 85 battery shears with AP 300 battery, a two-handed billhook, and a machete were used. While in late cleaning Stihl MS 261 petrol chainsaw and Stihl MSA 200 battery chainsaw with AR 3000 backpack battery were used (Table 1).

Four male forest workers on four worksites were involved in the measurements ranging from 35 to 59 years.

2.2. Worksites

The first two worksites represented early forest cleaning conditions, and the second two worksites represented late forest cleaning (Table 2).

2.3. Work dynamics, time and motion study

On all worksites, workers were instructed to work with respect to the defined work dynamic which was 30 min of work followed by 15 min of rest, with one 30 min rest after 4 working intervals. Workers would not change the tool in one working day which lasted 6 hours and 15 minutes, of which 4 hours were working intervals. Working intervals with tools that could be used or held in more than one way were filmed using a small hand-held action camera in order to perform time and motion study. This resulted in a total of 40 hours of video material. A total of 8 hours of working intervals using a two-handed billhook, 16 hours of working intervals using a battery chainsaw, and 16 hours of working intervals using a petrol chainsaw were recorded. Machete and battery shears were always used one-handed and those working intervals were not subjected to video recording. However, in all the working intervals in early forest cleaning, a number of swings/cuts was obtained using a simple mechanical click counter. That was done in order to simulate the same work tempo when measuring vibration levels generated by those tools.

Time and motion study was required in order to accurately assess daily vibration exposure in the tools that are used in more than one way. Huber et al. (2021) in their study estimate that cutting work while using petrol chainsaw and battery chainsaw in cleaning accounts for one-third of total productive time. A work sampling method was used on the obtained video recordings in order to calculate relative shares of different work elements within 4 hours of working intervals daily. During a short review and with experience from the previous research (Bačić et al. 2020), an approximate percentage of perceived working activities within one working interval was determined, and after that, the review of the entire recordings was started using the method of work sampling. For a 95% confidence interval, the required number of observations and recordings of work elements in one working day was calculated using equation 1.

$$N = \frac{1600 \times (1 - p)}{p} \qquad [1]$$

N – required number of observations;
p – percentage share of the least represented work element (calculated by previous short video review).

The observation interval was calculated from the ratio of the total duration of the video recordings in seconds

Table 1. Main tool features.

Tool	Features
ASA 85 battery shears	Mass of 0.98 kg, maximum cutting diameter 45 mm, declared vibration level of 2,5 m/s^2
Two-handed billhook	Length of 125 cm, mass of 1.43 kg, beechwood handle
Machete	Length of 61 cm, mass of 0.4 kg
MS 261 petrol chainsaw	Mass of 5.2 kg, bar length of 37 cm, *Rapid Super* chain, declared vibration level of 3,5 m/s^2 on both of the handles
MSA 200 battery chainsaw	Mass of 3.3 kg, bar length of 30 cm, *Picco Micro* 3 chain, declared vibration level of 4,6 m/s^2 on the front and 3.9 m/s^2 on the rear handle

Table 2. Worksite description.

Location	Description
Worksite 1	A young stand of common beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* Matt.) with admixtures of sycamore maple (*Acer pseudoplatanus* L.) and european ash (*Fraxinus excelsior* L.) in the developmental stage of young trees. The terrain was of southern exposure, with a slope of 9–14%.
Worksite 2	A young stand of pedunculate oak (*Quercus robur* L.), common beech (*Fagus sylvatica* L.), and common hornbeam (*Carpinus betulus* L.) in the developmental stage of young trees with developed weed vegetation on the entire surface. The terrain was without slope.
Worksite 3	Young stand of common beech (*Fagus sylvatica* L.). Other types of trees include common hornbeam (*Carpinus betulus* L.), common birch (*Betula pendula* Roth), and sycamore maple (*Acer pseudoplatanus* L.). The stand was in the developmental stage of young trees. The soil was covered with leaves, without bushes and ground growth. The presence of common birch of larger breast diameters was pronounced. The terrain was of southwestern exposure, with a slope of 8–12%.
Worksite 4	A young mixed stand of pedunculate oak (*Quercus robur* L.), european ash (*Fraxinus excelsior* L.), field maple (*Acer campestre* L.), and field elm (*Ulmus minor* Mill.) mixed with common hornbeam (*Carpinus betulus* L.), white willow (*Salix alba* L.), and fruit trees. The developmental stage was of young trees. The stand was medium to densely overgrown, with a heterogeneous mixture-quality ratio. The soil was overgrown with ground growth and hawthorn (*Crataegus* spp.) and blackthorn (*Prunus spinosa* L.) bushes. The terrain was without slope.

and the required number of observations for the least represented work element. For videos of early cleaning (only with a two-handed billhook) the observation interval was 8 seconds with 2 perceived elements, while for videos of later cleaning with a petrol chainsaw it was 3 seconds with 5 perceived elements, and while working with a battery chainsaw 26 seconds with 2 percieved elements. As the recordings took place over two days, the average time shares of the work elements were used in determining the vibration exposure. A total of 25,008 observations were made. The daily duration of one work element was calculated by multiplying its average time share by 4 hours of total working time.

2.4. Vibration level measurement and vibration exposure calculation

The process of determining daily vibration exposure is very complex if the daily work consists of several work elements of different durations in which vibrations of different levels occur (McGeoch et al. 2005). All-day measurement of daily vibration exposure during real-time cleaning work is extremely demanding and can lead to questionable results. The reason for this is difficult working conditions, dense vegetation, questionable battery life of the vibrometer, the need to fix the accelerometer on the tool handle, and very likely interruptions that would jeopardize the accuracy of the results. Therefore, in this study, it was decided to approach the measurement of vibration in controlled conditions. After determining the relative shares of characteristic work elements within the daily working intervals, vibration levels in these elements were measured. The instrument and equipment used in the measurement complied with the ISO 8041:2017 (2017) standard, and a Brüel & Kjaer 4447 vibrometer was used in combination with a three-axial accelerometer type 4520-002 and UA 3016 and UA 3017 mounts fastened with plastic ties and positioned in the immediate vicinity of the operator's hand (Fig. 1). Simulation of work in controlled conditions with one-handed tools was performed with the right hand as the dominant. The vibrometer was calibrated by an accredited company, and the measurement was performed according to the recommendations of ISO 5349-1:2001 (2001) and ISO 5349-2:2001 (2001) standards.

In the case of two-handed work with a billhook, vibrations were measured twice at the right-hand and left-hand grip positions. In other cases of early forest cleaning (one-handed work with a billhook, work with a machete and work with battery shears), vibrations were measured at one position. Because tools in early cleaning generate vibrations such as shocks that are extremely short in duration where it is very difficult to determine the exposure time, the following approach to vibration level recording was applied. It was necessary to know the daily average number of interventions (strikes/cuts), i.e. the tempo of felling so that while measuring vibrations in controlled conditions, the same number of interventions can be simulated in a certain time interval. Measurement of the vibration level on the tools used in the early cleaning was performed three times for one minute, simulating the tempo of felling recorded at individual sites. The UA 3016 accelerometer mount was used. The measurement was performed at FTRC (Forest Training and Research Center) Zagreb on a forest gap overgrown with black locust (*Robinia pseudoacacia* L.) and black elderberry (*Sambucus nigra* L.). The diameters of the cut trees were varied, from 2 to 5 cm, but suitable for the tools used. When calculating the A(8) value, an exposure time of four hours, i.e., total daily time of working intervals, was used.

Vibrations on chainsaws used in late cleaning were measured on both handles. Since chainsaws are two-handed tools, it is assumed that both hands of the worker are on the intended handles of the chainsaw during the cutting. When recording vibrations on the battery chainsaw, since the electric motor does not work during carrying and no vibrations are produced, the measurement

Fig. 1. Vibration measurement on the tools used in early cleaning.

was performed only during the cutting. The petrol chainsaw, which uses a two-stroke engine, runs continuously regardless of the work element, so the measurement was performed in six measuring combinations that coincide with the perceived five work elements.

While measuring the level of vibration on chainsaws, the shortness of cutting time was also a challenge. According to the ISO 5349-2:2001 (2001) standard, one measurement should not be shorter than 8 seconds. To prolong the cutting time, parts of the tree with a diameter of 8 to 20 cm, species of common hornbeam (*Carpinus betulus* L.) were stacked on top of each other and fixed and cutting took 30 seconds continuously (Fig. 2). Chainsaws were equipped with new chains. The UA 3017 accelerometer mount was used during the measurement. The measurement was performed at FTRC Zagreb. Vibrations during cutting were recorded three times for 30 seconds. Vibration recording on a petrol chainsaw at idle was also performed on three occasions of 30 seconds each. The arithmetic mean of the three repeated measurements was calculated as the final vibration total value.

Daily vibration exposure A(8) is the eight-hour energy equivalent of the frequency-weighted vibration total value, calculated by combining work element duration data obtained in the time and motion study and vibration total values measured under controlled conditions using equation 2.

$$A(8) = \sqrt{\frac{1}{T_0}\sum_{i=1}^{n} a_{hvi}^2 \times T_i} \qquad [2]$$

A(8) – daily vibration exposure;
a_{hvi} – vibration total value for *i* work element;
n – total number of work elements;
T_0 – reference working time of eight hours (28800 s);
T_i – duration of *i* work element.

A(8) is calculated and expressed for each hand separately for tools that are handled by hands. The total exposure time when working with a chainsaw was set at 4 hours, while when working with a battery chainsaw, the average daily cutting time, recorded in time and motion study was used. The reference arm was the one with the highest A(8) value, and the final results were compared with the limits defined in the EU Directive 2002/44/EC (2002.

3. Results and discussion

3.1. Time structure of working intervals

The time structure of working intervals is one of the key parts of estimating daily vibration exposure. Different levels of vibration occur on the left and right arm during different work elements in a working interval, and in order to estimate the daily vibration exposure as accurately as possible, it was necessary to obtain the duration of these elements.

After a brief review of the video recordings, two work elements were identified during the early cleaning with the two-handed billhook: one-handed striking (right hand), and two-handed striking. Forest cleaning with a billhook was divided into two work elements due to the assumption that different levels of vibration occur depending on how many hands are on the handle of the tool. In early cleaning, the worker had the choice to use only the right hand or both hands. He used both hands about three-quarters of the time (Table 3). By using both hands, the worker facilitates the work of striking and cutting, while one-handed work with a two-handed billhook was tiring and required great strength. During one-handed work, the worker used his left hand to bend the tree to make it easier to cut and, after cutting, used the same hand to remove the cut part of the tree.

Table 3. Time share of work elements in working with a two-handed billhook.

Work element	Day 1	Day 2	Avg.	Avg. [%]
		[min]		
Two-handed striking	176.00	173.73	174.87	72.86
One-handed striking	64.00	66.27	65.13	27.14
Total	240	240	240	100

Fig. 2. Vibration measurement on the chainsaws used in late cleaning.

While using battery shears and a machete, the worker always used only one hand to cut, i.e. detailed time and motion study wasn't required. In addition to the results of the work sampling method on both the chainsaws and a billhook, one of the results was the average work tempo with tools in the early cleaning (Table 4). In both observed locations, while working with hand tools (billhook and machete), on average, a larger number of attempts were made to make cuts than while working with battery shears. To cut the tree with hand tools, it was not necessary to adjust the tool as with battery shears, where the blade had to be pressed firmly against the tree at the selected location. So cutting with hand tools was more fluent because it did not require great precision. Nevertheless, cuts with hand tools and cuts with battery shears were not comparable in terms of performance because they do not represent the number of trees cut down. With hand tools, several strikes to cut down one tree were sometimes required, and in some cases, it was also possible to cut down several thinner trees in one swing. In most cases, battery shears cut down one tree with one attempt.

Table 4. Average work tempo with tools in the early cleaning.

Location	Worksite 1	Worksite 2
Two-handed billhook	27 strikes/min	—
Machete	—	23 strikes/min
Battery shears	26 cuts/min	19 cuts/min

Late cleaning with a petrol chainsaw consisted of five work elements: cutting, carrying with both hands, carrying with the right hand by the front handle, carrying with the left hand by the front handle, and carrying with the right hand by the rear handle, noting that the chainsaw did not turn off while carrying. Table 5 shows that in both worksites where cleaning was performed with chainsaws, the relative share of cutting time is slightly more than one third, which coincides with the results of a German study (Huber et al. 2021) while the rest of the time the worker carried a powered chainsaw in multiple ways with a significantly higher share of carrying with both hands. The diameter of the trees and their spacing in this case dictate the time structure of working intervals. At Worksite 3, a large proportion of felled trees were above 15 cm in diameter at the position of the first cut, and 20 cm at the position of the final cut in the stump. Therefore, the relative share of cutting in this location was slightly higher. But despite significant differences in stand characteristics between the two observed worksites, the share of cutting was approximately equal. The most common way to carry a chainsaw was to use both hands, which was also approximately equal in both locations. Due to the dynamic nature of cleaning work, the worker was generally unable to place the chainsaw on the ground and rest his hands. During the field measurement, this scenario did not occur. Because the worker moved to another tree very soon after cutting and had to approach the next tree with a chainsaw, he couldn't rest it on the ground or a fallen tree, such as in delimbing work. Judging by this, the result that indicates the largest relative share of carrying a saw with both hands is logical for the simple reason that in this way the worker made his job easier by using both hands to hold a heavy tool. Carrying a saw with one hand by the front handle is an individual matter of each worker which mainly depends on the dominance of the hand. However, a slightly higher share of using the left hand while carrying a chainsaw can be explained by the fact that the left hand was already on the front handle of the chainsaw when cutting, and it stayed there during the transition to carrying. Transferring a chainsaw to the right hand occurs if, for various reasons, a slightly more extended period elapses between the felling of two trees. In this case, the worker switched hands due to fatigue caused by the static work of holding the chainsaw. In rare cases, the worker held the saw with his right hand by the rear handle. While holding the saw like this, the worker is mostly stationary and used his left hand to move the cut tree canopy.

When working with a battery chainsaw, since this type of chainsaw does not produce vibrations when carried, only two work elements were determined: cutting and carrying (Table 6). It should be noted that chainsaws are two-handed tools and it is understood that both

Table 5. Time share of work elements in working with a petrol chainsaw.

Work elements	Worksite 3				Worksite 4			
	Day 1	Day 2 [min]	Avg.	Avg. [%]	Day 1	Day 2 [min]	Avg.	Avg. [%]
Cutting	90.05	90.05	90.05	37.52	79.00	86.85	82.92	34.55
Carrying BH[1]	78.95	81.15	80.05	33.36	68.6	80.55	74.58	31.08
Carrying RF[2]	28.35	21.15	24.75	10.31	37.50	33.7	35.60	14.83
Carrying LF[3]	40.20	45.85	43.03	17.93	49.60	36.10	42.85	17.85
Carrying RR[4]	2.45	1.80	2.12	0.88	5.30	2.80	4.05	1.69
Total	240	240	240	100	240	240	240	100

[1] both hands; [2] right hand-front handle; [3] left hand front-handle; [4] right hand-rear handle.

Table 6. Time share of work elements in working with a battery chainsaw.

Work elements	Worksite 3				Worksite 4			
	Day 1	Day 2 [min]	Avg.	Avg. [%]	Day 1	Day 2 [min]	Avg.	Avg. [%]
Cutting	111.31	128.69	109.79	45.75	89.57	93.90	91.74	38.23
Carrying	108.26	131.74	130.21	54.25	150.43	146.1	148.26	61.77
Total	240	240	240	100	240	240	240	100

hands are on the handles when cutting. While working with a cordless saw, the cutting work took a little longer, approximately two-fifths within 8 working intervals daily. The longer cutting time, especially at Worksite 3, can be explained by the significantly slower chain of the battery chainsaw. Huber et al. (2021) found in their study that while working with a battery chainsaw, the share of cutting time is one-third of the productive time. However, in that study, a battery chainsaw with a significantly higher chain speed was used. The chain speed depends primarily on the chain pitch and the rotational speed of the drive motor. The two-stroke petrol chainsaw engine has a significantly higher maximum speed than battery chainsaws. For this reason, a petrol chainsaw chain develops a top speed of 26 m/s, while a battery chainsaw chain develops a top speed of 18.8 m/s. The higher relative share of cutting while working with a battery chainsaw is also caused by various cutting difficulties. Thinner trees or branches were bending in contact with a battery chainsaw chain that did not have enough speed to make a quick cut. Furthermore, a battery chainsaw chain is extremely thin, which resulted in frequent chain slipping during the first cut if the guide was not laid correctly on the tree, i.e. if it was slanted to the side.

3.2. Vibration levels and daily vibration exposure

While cleaning with a billhook, vibration levels were higher during two-handed operation. While using both hands, the speed of the swing, and thus the force of the impact on the wood, was higher, which caused higher recorded vibrations (Table 7). For this reason, one-handed work with a two-handed billhook creates significantly less vibration than work with a one-handed billhook that swings slightly faster, which is supported by a previous study (Bačić et al. 2020) where a vibration level of 19.34 m/s^2 was recorded on a one-handed billhook. The highest level of vibration was recorded while cleaning with a machete, which was expected. Namely, the machete, unlike a billhook, did not have a wooden handle that separates the metal blade, that is the source of the vibration, from the hand and reduced the transmission of vibration to the hands of workers. The role of the handle in vibration transmission is significant (Beckley 2019). The metal blade of the machete effectively conducted the vibrations created by striking the wood to the handle of the machete (worker's hand) which consisted of two mirror pieces of wood attached to the metal part. The small dimensions of the machete handle do not have a great ability to dampen the vibrations created (Kocjančić 2018). The level of vibration recorded while working with battery shears is extremely low. There is a minimal difference due to the two different work tempos at which the vibrations were recorded. Slightly higher vibration levels were recorded at a faster tempo with battery shears. Low vibration levels were the result of gentler operation with battery shears where the sources of vibration are short starts of electric motor and transmission, and the interaction of metal blades and wood, where there are no violent shocks that would create significant vibration levels.

Table 7. Vibration levels in tools used in the early cleaning.

Tool	Location	Work tempo [strikes or cuts/min]	Hand	Vibration total value – α_{hv} [m/s^2]
Billhook	Worksite 1	27	Right[1]	13.54
Billhook	Worksite 1	27	Right[2]	11.81
Billhook	Worksite 1	27	Left[1]	14.53
Battery shears	Worksite 1	26	Right	1.10
Machete	Worksite 2	23	Right	23.42
Battery shears	Worksite 2	19	Right	0.98

[1] two-handed operation (left hand above right); [2] one-handed operation (right hand).

When calculating the daily vibration exposure A(8) in the early cleaning (Table 8), the exposure time of four hours was used, although the effective working time with the tools used is not limited by the Ordinance on Occupational Safety and Health in Forestry (1986). In practice, workers rarely work longer than four effective hours in early cleaning due to unbearable heat and difficult working conditions. On the billhook, which is the only two-handed tool in early cleaning, it has been established that the right hand is the reference, so the results will be observed for the right hand. The higher recorded daily exposure on the right hand is logical because that hand was always in contact with the tool, regardless of one-handed or two-handed operation, while the left hand is not in contact with the tool in one-handed operation. Daily exposure to vibrations on the right (and left) hand while working with a billhook significantly exceeded the limit value of 5 m/s^2, and according to EU Directive 2002/44/EC (2002) such work should not be continued. At the level of vibration occurring on the right hand in the two-handed operation, it took 16 minutes of work (continuous striking) to reach an exposure of 2.5 m/s^2 or an action value, and 65 minutes of work to reach a limit value of 5 m/s^2. On the right hand in the one-handed operation, it took 22 minutes to reach the action value, and 86 minutes to the limit value. Daily exposure to vibrations was highest while working with a machete, and the result obtained was similar to the result from the previous study (Bačić et al. 2020) on a one-handed billhook of 13.7 m/s^2. The calculated value was extremely high, and it took only 5 minutes of work to reach the action value, while the limit value took 22 minutes of work. While working with battery shears, for both observed locations, a very low daily exposure to vibration was calculated, and it took over 24 hours to reach the action and limit values. It should be kept in mind that the shock (vibration) while working with hand tools is of very short duration and that the frequency characteristics of this type of vibration were not investigated in this paper. This study relies on frequency weighting algorithms that are incorporated into the used instrument (vibrometer) and thus find these results relevant.

Table 8. Daily vibration exposure in tools used in the early cleaning.

Tool	Billhook	Machete	Battery shears	
Location	Worksite 1	Worksite 2	Worksite 1	Worksite 2
Right hand A(8)	9.3 m/s^2	16.6 m/s^2	0.8 m/s^2	0.7 m/s^2
Left hand A(8)	8.8 m/s^2	—	—	—

The petrol chainsaw generated vibrations in all work elements, while the battery chainsaw vibrated only when cutting. Vibration levels are presented according to the measurement combinations (Table 9). While cutting with a petrol chainsaw, higher levels of vibration were recorded on the front handle which is not in line with the results of Goglia et al. (2012) where higher levels of vibration in cutting are recorded on the rear handle (Stihl MS 260) and the results of a German study (Huber et al. 2021) where a Stihl MS 201 C chainsaw is used. When carrying a chainsaw with both hands, a higher level of vibration was recorded on the rear handle, as noted by Goglia et al. (2012) but with higher values. Furthermore, the results obtained also coincide with the above study while carrying a chainsaw with one hand (left and right) by the front handle and the right hand by the rear handle where the highest level of vibration was recorded. Compared to the declared vibration levels of 3.5 m/s^2 on both handles (MSA 200 C-B 2022), higher vibration levels were recorded in all measuring combinations for petrol chainsaws.

An interesting result is that slightly higher levels of vibration while cutting were recorded on a battery chainsaw in contrast to the Slovenian study (Poje et al. 2018) and the German study (Huber et al. 2021). In these studies, higher vibration levels are also recorded on the front handle of the battery chainsaw. The Makita DUC302Z battery chainsaw is tested in a Slovenian study and the Stihl MSA 220 C in a German study. A probable reason for the increase in recorded vibration levels, apart from the different types of chainsaws tested, is the fact that the battery chainsaw used in this study had a lower mass than the mentioned chainsaws causing higher vibration levels at work (Malchaire 2020). The observed chainsaw had less mass because it did not use a small battery that is stored in the housing, which increases its total mass, but instead used a backpack battery. It should be borne in mind that different vibration recording methods and different types of chainsaws can also give different results of vibration level measurements. In this research, the methods and conditions of vibration recording were designed to represent the actual field conditions as faithfully as possible, while meeting the applicable measurement standards. Furthermore, the battery chainsaw used in this study was not equipped with a conventional anti-vibration system which is common for battery chainsaws that do not produce high levels of vibration due to the circular motion of their drive motor. By the interaction of chain and wood which is a heterogeneous material, certain deviations in the measured vibration levels occur. The recorded vibration levels on the battery chainsaw were higher than the declared 4.6 m/s^2 on the front handle and 3.9 m/s^2 on the rear handle (MSA 200 C–B 2022), but with an approximately similar ratio between the front and rear handle.

Table 9. Vibration levels in chainsaws used in the late cleaning.

Chainsaw type	Measuring combination	Work element		Hand		Handle		Vibration total value $-\alpha_{hv}$ [m/s^2]
		Cutting	Carrying	Left	Right	Front	Rear	
Petrol chainsaw	1	×		×		×		4.05
	2	×			×		×	3.62
	3		×[1]	×		×		3.57
	4		×[1]		×		×	5.62
	5		×[2]		×	×		5.69
			×[2]	×		×		5.69
	6		×[2]		×		×	6.30
Battery chainsaw	1	×		×		×		5.15
	2	×			×		×	4.29

[1] carrying with one hand; [2] carrying with both hands.

According to the results of daily exposure to vibration while working with a petrol chainsaw (Table 10), higher exposure was recorded on the right hand, while the left hand was more exposed on the battery chainsaw, and they are considered a reference. In both observed locations, lower exposure to vibrations was observed while working with a battery chainsaw as in previous studies (Colantoni et al. 2016; Neri et al. 2018; Poje et al. 2018). Vibration exposure while working with a petrol chainsaw at both worksites exceeded the exposure action value of 2.5 m/s^2, while when working with a battery chainsaw at Worksite 3, the estimated exposure was exactly at the exposure action value. It took 1 hour and 53 minutes to reach the exposure action value with a battery chainsaw, while it took 7 hours and 32 minutes to reach the exposure limit value. Differences in daily vibration exposure (on the same chainsaw) between the two worksites are minimal and stemmed from differences in the relative time shares of work elements.

Table 10. Daily vibration exposure in chainsaws used in the late cleaning.

Chainsaw type	Petrol chainsaw		Battery chainsaw	
Location	Worksite 3	Worksite 4	Worksite 3	Worksite 4
Left hand A(8)	2.8 m/s^2	2.8 m/s^2	2.5 m/s^2	2.3 m/s^2
Right hand A(8)	3.1 m/s^2	3.2 m/s^2	2.0 m/s^2	1.9 m/s^2

4. Conclusion

Vibration levels and daily vibration exposure while cleaning with battery shears are many times lower compared to cleaning with a two-handed billhook and machete. The work tempo with all the observed tools in the early cleaning is similar, but the technique and mode of operation of the tool are quite different. Cutting a tree using battery shears was fluent, without jerks and sudden movements, while cutting with hand tools was quite the opposite, moreover, the greater the force of impact - the better the effect of cutting. High forces during work and sudden stops of tools when striking wood had caused very high recorded vibration levels in hand tools, and consequently high daily exposure.

Although the recorded vibration levels on the used battery chainsaw were higher than on the petrol chainsaw, the daily exposure was lower. The complete absence of vibrations caused by the rotation of the drive motor in the work element of carrying the battery chainsaw had an extremely large impact on daily exposure. Due to the slower chain, the duration of the cutting with a battery chainsaw was somewhat longer, and it can be concluded that using newer models of battery chainsaws, with higher chain speed, would shorten the total duration of the cutting at the expense of increasing the duration of carrying, which would additionally lower the daily vibration exposure.

The recorded vibration levels, as well as the daily exposure, were many times higher in the early cleaning with a billhook and machete than in the late cleaning with a chainsaw. In operational forestry, workers with reduced working ability are excluded from working with a chainsaw due to a diagnosed white fingers disease and the fact that the chainsaws are vibrating tools. Some of these workers are transferred to silvicultural work with hand tools such as billhook and machete which are not considered vibrating tools. From the above mentioned, it can be concluded that a detailed revision in the classification of tools is needed, considering their ability to produce and transmit harmful vibrations to the operator and that using the current classification can be unfavorable for the worker and his health.

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