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Workload, Exposure to Noise, and Risk of Musculoskeletal Disorders: A Case Study of Motor-Manual Tree Feeling and Processing in Poplar Clear Cuts

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Abstract: Motor-manual tree felling and processing (MMTFP) is among the most used options in timber harvesting operations and it is formally known to be a heavy job exposing the workers to safety hazards and harmful factors. Nevertheless, both workload and exposure depend on many operational, organizational, and worker-related parameters. Few studies have evaluated the ergonomics of such operations and fewer have been carried out using an integrated approach able to collect and interpret data for more than one ergonomic parameter. This study evaluated the ergonomic conditions of task-based MMTFP operations in flatland poplar forests by the means of workload, exposure to noise, and risk of musculoskeletal disorders. A fully-automatic approach was used to collect and pair the heart rate and noise exposure data that was complemented by video recording to collect postural data. Workload experienced by the worker was evaluated in terms of heart rate reserve (%HRR), indicating a heavy load during the productive time (%HRR = 46%); exposure to noise was calculated at the task and study level, exceeding (LAeq = 97.15 dB(A); $L_{EX,8h}$ = 96.18 dB(A)) the acceptable limits; and the risk of musculoskeletal disorders was evaluated using the concepts and procedures of the Ovako Working Posture Analysis System, indicating a high postural risk index (PRI = 275), which can cause musculoskeletal disorders (MSD). For more conclusive results, the research should be extended to cover the relevant variability factors.

Keywords: forest operations; motor-manual work; ergonomics; workload; exposure to noise; musculoskeletal disorders; automation.

1. Introduction

Wood it is one of the most used industrial materials, contributing to economic development and growth, and at the same time providing many employment opportunities. In the European Union (EU), 58% of the harvested lignocellulosic biomass is processed by the forestry-related industries, accounting for 7% of the EU's processing industry Gross Domestic Product and employing 3.5 million of people [1]. In order to be delivered to the markets, from an operational standpoint, wood procurement involves a series of transformations aiming to modify its shape and location which makes it either an intermediate or a final product [2]. A significant part of such value-adding transformations is taking place in the forests by the use of various harvesting systems whose mechanization level depends on several factors [3], including the economic condition of a given area or country, a fact which places the Eastern European countries in the category of low to moderate mechanization levels used in forest operations [4]. While highly-mechanized technology exists in such countries, its use is rather scarce due to various reasons such as the reduced forest accessibility [5,6] or the limitation of harvests to small areas and low extraction intensities [7]. In these circumstances, an important part of the timber harvesting work is done manually or motor-manually, a fact that could affect the forest operations' sustainability, at least from the ergonomic point of view, since the used harvesting systems need to ensure the workers' safeguarding and protection of undue risks [8], at the same time being compatible with the workforce [9]. Therefore, such contexts could also contribute to workforce migration to other industries, reducing the employment rate in forestry [10].

On the one hand, motor-manual tree felling and processing is still one of the most used options in timber harvesting operations judging by the amount of scientific publications on the subject [11]. This situation could be attributed to several factors related to the equipment used, such as the acceptable purchasing and operation costs, a relatively long-life span [12], compatibility with steep terrain, adaptability to a wide range of tree sizes and species [11], and small extraction intensities [13]. On the other hand, motor-manual fellers are required to work under open sky, being exposed, in many cases, to extreme temperatures [14], which makes the chainsaw work particularly difficult. Similar to other kinds of manual work in forest operations [15–17] and judging by the amount of time spent in tasks which involve movement [13,18], motor-manual fellers are required to cover long distances during a work day and to climb high slopes, which are known factors that affect the work difficulty experienced by the forestry workers [19], while the nature of the job itself, shaped by the tasks to be carried out, causes an intense physical strain [20]. In addition, motor-manual work in forest operations is exposing the operators to harmful factors such as high noise [21] and vibration [22,23] doses, as well as to increased risks of musculoskeletal disorders (MSD) [24,25] due to the specific work postures of such operations [26–28]. In time, exposure to noise can cause hearing loss [29,30], while the exposure to vibration can cause vascular disorders [31]. Moreover, motor-manual felling is known as one of the jobs causing frequent health impairment or even fatal injuries [32–34], which are often associated with the workers' behavior, organizational setups [35,36], and with taking unnecessary risks by disobeying safety procedures [35,37].

Nevertheless, the exposure to such harmful factors, as well as the difficulty of the work experienced by operators, depend to a great extent on the particularities of operational conditions, which vary widely in forestry [38] and which, by the recommended [2] and adopted work procedures, as well as by the specific time management, contribute to a given distribution in time of the work tasks. From this point of view, a tree felling and processing work cycle can be more or less complex [2]. At the same time, the engine's utilization time, which causes the exposure to noise and vibration, varies quite widely as an effect of particular operational conditions in terms of tree size, which can generate more [18] or less [13] time spent in the chainsaw operation.

Therefore, in time and motion studies, as well as in ergonomic assessments carried out in forest operations, there are many operational variables that could affect the predictions that are made [38]. Often, it is difficult to survey several ergonomic parameters and to attribute their estimates to the factors that caused them because this involves a significant logistic and data processing effort. For instance, postural assessment of a given job is often made based on visually-interpreted data collected in the field, such as video files that are used to extract pictures needed in the analysis [26,39], while in time and motion studies, analysis of video data can take four to six times more time compared to the time covered by the data itself [40]. Nevertheless, many of the ergonomic factors are affecting the work performance and health of the subjects [41]. Therefore, their joint evaluation could bring many benefits in understanding the difficulty and the risks associated with a given job.

Judging by the variability of operational conditions in which the chainsaws are used [10], few studies have addressed the on-the-job ergonomics of motor-manual operations, while many of them have focused on the characterization of a single ergonomic parameter [42].

This work aimed to evaluate the ergonomic conditions of motor-manual tree felling and processing by a task-based case study implemented in a poplar clear cut. The main objectives of the study were set to: (i) evaluate the workload of the feller by measurements carried out on the heart rate; (ii) evaluate the exposure to noise as specific to tree felling and processing tasks; and (iii) evaluate the risk of musculoskeletal disorders by estimations of the Postural Risk Index (PRI) under the Ovako Working Posture Analysis System (OWAS). To characterize the operational conditions and the inputs, which can help in the ergonomic assessment of the job, secondary objectives of this study were set to: (iv) measure the time consumption and estimate the productivity involved in tree felling and processing operations; and (v) measure the fuel and lubricant inputs.

2. Materials and Methods

2.1. Study Location, Equipment Description and Work Organization

Motor-manual tree felling and processing operations were carried out in May of 2017, in a 30-year old hybrid poplar (*Populus x euroamericana* (Dode) Guinier) dominated stand located in compartment 89A, management unit 4 Rast, near Rast village, Dolj county, Romania.

In the area, forests are managed by the Poiana Mare Forest District which is a territorial unit of the Romanian Forest Administration—Regia Naţională a Pădurilor - RNP Romsilva. In Romania, hybrid poplars are mainly cultivated on flatlands, near the Danube river, main rivers, and Danube Delta, on a total area that is estimated to be about 50,000 hectares [43]. Such forests are characterized by a remarkable growth that can sometimes exceed 30 m^3 per year and per hectare [43]. Typical for them is a production cycle which is rather short, ending at 25 years, when the main harvests are implemented by clear cuts on blocks of up to three hectares. Nevertheless, due to various reasons related to forest management, some of the hybrid poplar forests are harvested at ages higher than 25 years, as in the present study.

A 2.81-hectare felling block was designated for clear fell harvesting, being located at 43°51′17′′ N–23°20′09′′ E, 110 m above sea level, on a flat land (Figure 1, Table 1), near the Danube river.

Figure 1. Study location.

Table 1. Description of the felling block.

Parameter	Measurement Unit	Value
Area	ha	2.81
Slope	%	<1
Stand age	years	30
No. of harvestable trees	-	393
Composition	%	100 poplar [1]
Harvestable stock, over bark	m^3	1519
Harvestable stock, under bark	m^3	1398
Average tree volume, over bark	m^3·tree^{-1}	4.83
Average DBH	cm	63
Average heigth	m	39
Silvicultural system	-	Clear felling, small blocks
Harvesting method	-	Combination of tree length and cut to length
Harvesting system	-	Motor-manual tree felling and processing & skidding

[1] Disseminated: mulberry tree. DBH: diameter at the breast height.

The harvestable stock was contracted by a private company which carries-on jobs on a regular basis in the area. Harvesting operations were carried out by a team consisting of two men: one operated an agricultural tractor equipped for forest operations (Deutz DX 6.30, Deutz-Fahr, Germany) and took care of the winching, skidding, and landing operations; while the other one carried out tree felling and processing tasks with only minor interventions at the landing to supplementary buck the forked logs. Such harvesting systems are typical for the area because they allow the extraction of logs with a length of about 10 m, limiting the tree bucking in the forests, on the one hand, and correlating the size and the weight of the logs with the tractor traction capabilities, on the other hand.

To fell, debranch, and buck the trees, the chainsaw operator used a 3.4 kW Stihl MS 362 two-stroke mechanical chainsaw weighing 5.9 kg, which was equipped with a 40-cm sawing blade. Characteristic to this study was the fact that before tree felling and processing, the feller had to clear the work place around the tree of brush vegetation (mainly *Amorpha fruticosa* (L.)) as a prerequisite to ensure the safety conditions required in tree felling operations [2].

The feller had a substantial work experience in forest operations (more than 20 years), with the majority of his jobs carried out in tree felling and the processing of poplar stands located in flat terrains.

2.2. Data Collection

The field data collection activity covered three operational days, namely the 16th, 18th, and 19th of May 2017, during which time a total of 31 trees, representing roughly 10% of the harvestable volume, were felled and processed.

Before the study, a researcher explained the scope of the study and the intended use of data to the harvesting crew and obtained the verbal consent to carry out the study. The motor-manual tree feller was instructed to carry on his job as usual, and the way in which the data collectors work, as well as the intended use of the data, were described to him in detail. Following the instructions, he agreed to carry the instruments during the time spent on-the-job in the field operations, but he disagreed to wear the heart rate sampler during his off-the-job, personal time. At the study time, the feller was 42-years old and he declared that he was a non-smoker, as well as the fact that he does not drink alcoholic beverages and usually drinks one coffee per day, in the morning.

The average air temperature for the study time was calculated based on the data collected from the nearest meteorological station—Calafat (Dolj, Romania), located at 43°59′06′′ N–22°56′46′′ E, 62 m above sea level, at 33 km of the study site, and it was rated at 19 °C, ranging from 12 to 22 °C. Therefore, the motor-manual feller was assumed not to be under heat stress [41].

Field data collection was designed to simultaneously capture information about the time and fuel consumption, operational variables, physical strain, exposure to noise, and risks of musculoskeletal disorders, while minimally affecting the typical way of doing work by delays caused by the study. This supposed the implementation of a detailed time and motion study that was designed to describe specific tasks and to evaluate the elemental time consumption based on the general concepts and recommendations described in [38,44]. However, the study was not designed to model the dependence of time consumption as a function of operational variables, a reason for which only the minimal set of operational variables made the subject of measurement during the observations.

To be able to describe the exposure to noise during specific tasks, the concept of dividing the studied time into subsequent work elements also took into consideration the state of the chainsaw engine. This approach is a good option in motor-manual studies, where one needs to account for such separations either to determine the engine utilization rate [45] or to evaluate the ergonomic conditions.

The total study time (TST, s) was assumed to be conceptually divided into two main categories: productive time (t_P, s) and non-productive (t_{NP}, s). In this concept, the first category grouped all the work elements which supposed the effective implementation of operations, that are usually taken into consideration when assessing the ergonomic conditions of a given job [39,46,47]. This time category was also used to estimate the net productivity and efficiency. The second category contained all the time spent during non-productive events and tasks such as delays, preparatory time, rests, and study delays and it was used to estimate the gross productivity and efficiency in the given conditions. Therefore, the total study time was divided into work elements as described in Table 2, and the time consumption data was collected on paper sheets using the continuous timing method [44].

Table 2. Description of work and time elements that were specific to the study.

Work Element (Engine State)	Abbreviations	Description
Work preparation (engine off)	WP t_{WP}	The time spent to prepare the work, consisting of taking the tools, fuels, lubricants and manitenance kits from their storage place and movement from the resting place to the landing. Includes the placement of the used dataloggers.
Moving with chainsaw off (engine off)	M_OFF t_{M_OFF}	The time spent in moving from landing into the cutting block, between the trees to be felled, from the felling place to the felled tree and from the cutblock to the landing
Rest pause (engine off)	RP t_{RP}	The time spent for personal rest, without any movement, including the time spent to measure the heart rate at rest
Meal time (engine off)	M t_M	Time spent to have the meal which included small movements
Study delay (engine off)	SD t_{SD}	Delays caused by the study such as those needed to measure the dendrometric characteristics of the trees and to measure the fuels and lubricants, including refuelling
Finishing the work (engine off)	WF t_{WF}	The time spent to get back at the resting place and to take down the used dataloggers
Moving with chainsaw on (engine on)	M_ON t_{M_ON}	The time spent in moving between the trees to be felled and from the felling place to the felled tree
Clearing the workplace (engine on)	CW t_{CW}	The time spent to clear the workplace by removing the brush and other vegetation around the tree
Notch cutting (engine on)	NC t_{NC}	The time spent to make the notch, including small movements around the tree
Tree felling (engine on)	TF t_{TF}	The time spent to make the felling cut, including small movements around the tree
Clearing the stump and the bole (engine on)	CSB t_{CSB}	The time spent to level the stump and the tree end by removing wood fiber following the felling
Debranching (engine on)	DB t_{DB}	The time spent to move along the felled tree and to remove the branches
Tree bucking (engine on)	TB t_{TB}	The time spent to move along the tree and to make cross-cuts
Bucking at landing (engine on)	BL t_{BL}	The time spent to buck forked logs at landing including small movements to make the cuts
Technical delay (engine on)	TD t_{TD}	Delays caused by technical reasons such as those in which the blade was trapped into cuts which predominated in this study

Data describing the operational conditions of each observed tree was collected by a researcher who measured the diameter at the breast height (DBH, cm) and the diameter at the stump height (DS, cm) to the nearest centimeter using a forestry caliper. Production (P, m^3) of motor-manual tree felling and processing was estimated based on the over-bark volume input in the operations, using the average tree volume (TV, m^3) extracted from the harvesting block utilization act, as shown in Table 1, and the number of felled trees during the observations.

Total fuel mixture (FM, L) and chain lubrication oil (LO, L) consumptions were measured in the field using the general methods recommended in [38] and described by a similar study [48], with the difference that refueling took place at the free will of the feller. Unit fuel mixture (UFM, L·m^{-3}) and chain lubrication oil (ULO, L·m^{-3}) were computed at the office based on field recorded data and the estimated production.

Workload of the feller was evaluated based on the cardiovascular activity in terms of heart rate (HR, bpm), using a Polar V800 device (www.polar.fi) which was setup to collect data at a one-second sampling rate. The device consists of a pericardial strap equipped with a sensor able to sample the heart rate and to transmit it to a smartwatch worn by a given subject (Figure 2) via Bluetooth® technology, while the recorded data can be downloaded via the Polar FlowSync application (www.polar.fi) into a web-based data repository. The web-based tool enables data exporting in friendly computer-use formats such as .GPX and .CSV. In this study, the data from each of the observed days was transferred to the web-based repository, by synchronizing the watch to a computer at the end of each work day. At the beginning of each study day, the motor-manual feller was asked to stay in a comfortable posture for a period of 15 min with the strap mounted on the chest and the device switched on, to be able to collect data documenting the heart rate at rest.

Figure 2. Placement of dataloggers on the feller.

Exposure to noise was monitored using a sampling rate of one second by adopting the full day measurement strategy, using a procedure in line with the European legislation and relevant standards [49]. This was done by placing a small Extech® 407760 noise-level datalogger (Extech Instruments, FLIR Commercial Systems Inc., Nashua, USA) on the helmet of the feller at a distance of 10 cm aside his ear (Figure 2). Such devices are designed to meet the ANSI (American National Standards Institute) and IEC (International Electrotechnical Commission) 61672 Class 2 standards [50], being able to collect data on either a dB(A) or dB(C) scale and to export it via the dedicated software as .CSV files. In addition, they are able to label the collected data using the date and time of each observation, a feature which, along with the reduced size and weight, makes them suitable for monitoring motor-manual operations [45].

In addition, a researcher used a digital video camera to record the operations at random sampling intervals. The resulted video files were saved on the internal memory using a naming procedure that allowed their identification in a given study day. These files were used to evaluate the risks of musculoskeletal disorders (MSD) in the office phase of the study.

2.3. Data Processing and Analysis

Data collected during the time study was transferred from the paper sheets into an Microsoft Excel spreadsheet along with codes given for each of the observed tasks (Table 2), and the time consumption for tasks was then computed by difference as specific to the continuous time studying method [44].

Data downloaded from the noise-level datalogger (SL, dB(A)) and from the heart rate sampler (HR, bpm), respectively, were paired into an MS Excel spreadsheet using the date and time labels recorded for each observation (Figure 3). Following this procedure, a code describing the carried-out task (Table 2) was paired to each observation.

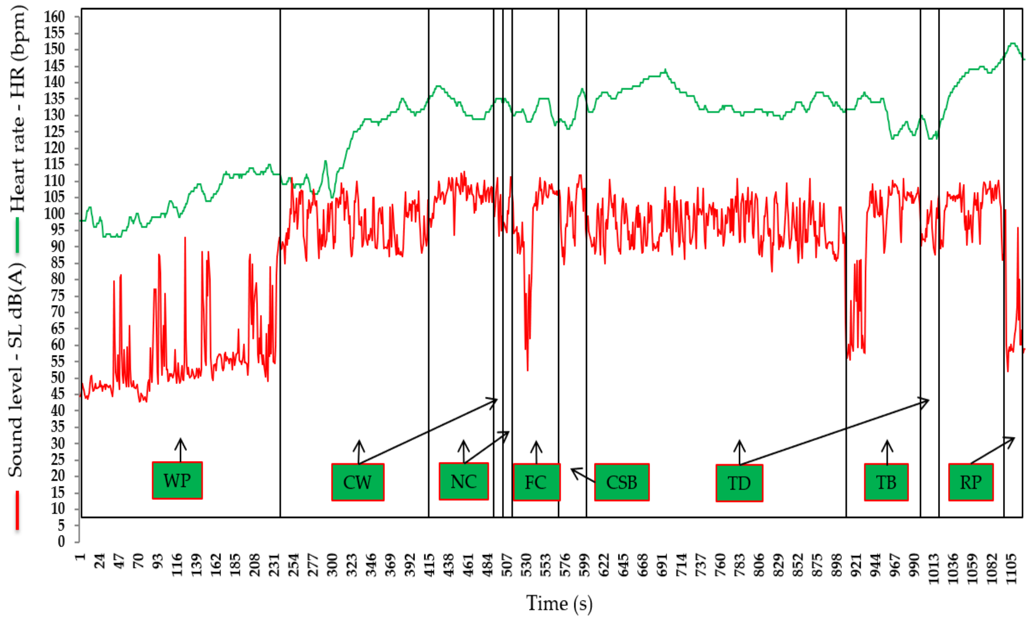

Figure 3. Conceptual framework of data pairing using the time labels and codes: WP: work preparation; CW: clearing the workplace; NC: notch cutting; FC: felling cut; CSB: clearing the stump and the bole; TF: technical delay; TB: tree bucking; RP: rest pause.

Summary descriptive statistics of the operational variables, fuel, lubrication oil, and time consumption were computed following the statistical procedures described in [38], as well as the examples provided by other similar time and motion studies [13,18]. Based on the production estimate and the productive and non-productive time consumption, both net and gross efficiencies (E_{NET}, E_{GROSS}, $h \cdot m^{-3}$) and productivities (P_{NET}, P_{GROSS}, $m^3 \cdot h^{-1}$) were estimated.

Workload of the feller was evaluated by considering the work tasks in which he operated using the approach of computing the heart rate increment and the heart rate reserve, based on the Equations 1 [20] and 2 [51]. Heart rate reserve is a common indicator used in describing the difficulty of work, especially in those work environments in which the use of more accurate and sophisticated ergonomic instruments is difficult. Therefore, it was used in many forest operation-related studies [19,20,52–56] and it represents a good estimator of the VO_2 indicator in forest operations [57] that is commonly used to predict the work intensity in general ergonomic studies.

$$\%HRIi = (HRwi - HRr)/(HRr) \times 100 \tag{1}$$

$$\%HRRi = (HRwi - HRr) \times 100/(HRmax - HRr) \tag{2}$$

where %HRIi is the heart rate increment calculated for the work task i or for the total study time; %HRRi is the heart rate reserve calculated for the work task i or for the total study time; HRwi is the working heart rate of the task i or of the total study time, calculated as the average number of beats per minute specific to task i or of the total study time; HRmax is the maximum heart rate calculated using the formula 220-age [51]; and HRr is the resting heart rate calculated as the minimum value of samples collected within a period of rest or the minimum value of the HR recorded during the study.

In forest operations, exposure to noise is affected, among other factors, by the engine state, as proven by previous studies [46,58,59]. The procedures used to process the data and analyze the exposure to noise were those described by the European legislation [49] and international standards for noise assessment. Evaluations were done based on the use of Equations 3–5, to determine the actual exposure to noise in given tasks and for the study, as well as to determine the normalized exposure for a nominal eight-hour day. The A-weighted equivalent continuous sound pressure level (LAeq, dB(A)), as well as the A-weighted noise exposure level normalized to a nominal 8-h working day ($L_{EX,8h}$, dB(A)), were computed for the tasks carried out by the motor-manual worker, following the data downloading and its systematization on work tasks, work days, and study level. This meant the use of simple MS Excel logical functions that attributed the recorded and computed values on tasks, using the task codes (Table 2) attributed by a researcher for the heart rate and sound pressure level samples.

$$\mathrm{LAeq}\ [\mathrm{dB(A)}] = 10\log\left[\frac{1}{\mathrm{T}}\sum_{\mathrm{t1}}^{\mathrm{t2}} \mathrm{t_i}\ \times 10^{0.1\ \times\ \mathrm{LAeqi}}\right] \tag{3}$$

$$\mathrm{LAeq,\ Te}\ [\mathrm{dB(A)}] = 10\log\left[\frac{1}{\mathrm{N}}\sum_{\mathrm{n\,=\,1}}^{\mathrm{N}} 10^{0.1\ \times\ \mathrm{LAeq,\ n}}\right] \tag{4}$$

$$\mathrm{L_{EX,8h}}\ [\mathrm{dB(A)}] = \mathrm{LAeq,\ Te} + 10\log\left[\frac{\mathrm{Te}}{\mathrm{8h}}\right] \tag{5}$$

where T is the time period, t_1 is the beginning time of a task, t_2 is the ending time of a task, t_i is the time interval characterizing task i, $LAeq_i$ is the A-weighted sound pressure in the interval t_i, LAeq is the A-weighted sound pressure in a given task or working day, LAeq, Te is the A-weighted sound pressure of a daily sample, n is the number of a given day, N is the total number of days, $L_{EX,8h}$ is the A-weighted noise exposure level for an eight-hour nominal day, and Te is the effective duration of the working day.

The Ovako Working Posture Analysis System (OWAS) was used to evaluate the risk of musculoskeletal disorders (RMSD). Originally, OWAS was developed for use in the work science and it is based on work sampling at variable or constant time intervals, being able to provide the frequency of the time spent in each of the observed postures [60]. It was designed to evaluate the posture of main body segments, which enables the attribution of a code which classifies the overall posture of the body and which helps further evaluate the discomfort of observed work and to undertake corrective measures as described by four action categories (AC). Given the potential high variability of the recorded postures and action categories, the general evaluation of a given job is based on a postural risk index (PRI) that is calculated as a weighted frequency of the action categories, in which the weighting factors are the frequencies of scores attributed to an action category [27,28,39,47] according to the Equation 6:

$$\mathrm{PRI} = ((f_1 \times 1) + (f_2 \times 2) + (f_3 \times 3) + (f_4 \times 4)) \times 100 \tag{6}$$

where f_1, f_2, f_3, and f_4 are the frequencies of scores in action categories 1, 2, 3, and 4, respectively, calculated as percentage of the total observations attributed to a given action category.

While OWAS cannot measure parameters such as the movement frequency and duration, and physiological recovery [61] and it cannot distinguish between static and dynamic work [26,61], it is characterized by several advantages such as the simplicity in use [60], capability to cover the whole body, reliability, and comparability of results [39].

To carry on with the analysis, the recorded video files were broken into frames that were extracted as still images at a one-second sampling rate, resulting in 8059 frames. Then, each frame was manually analyzed to compute the action category in which it fell. Only those frames in which all the body segments were visible and therefore could be analyzed were retained as valid, resulting in a number of 6329 analyzed frames. For each frame, the tasks undertaken by the motor-manual worker were coded by short descriptive text strings as described in Table 2, along with the general coding system of the back, arms, legs, and force exertion. These resulted in an MS Excel spreadsheet in which a simple Visual Basic for Applications logical code was used to assign the general postural code and the action category for each frame. Then, the action categories were sorted based on work tasks and the frequencies of scores for each action category were computed. Following that, the postural risk index was calculated for each work task and for the whole sample.

3. Results

3.1. Time, Fuel, Lubricant Consumption, and Productive Performance Estimates

The total observed time in this study was almost 18.63 h, standing for 67,052 observations made on the heart rate and sound pressure level. However, the productive time accounted for less than 34%, as shown in Table 3.

Table 3. Summary description of time, fuel, lubricant consumption, and estimates of productive performance, St.dev.: standard deviation.

Parameter	Minimum	Maximum	Mean ± St.dev.	Sum	Share (%)
Operational variables					
DBH (cm)	54	88	67.45 ± 8.14	-	-
DS (cm)	60	100	77.23 ± 11.17	-	-
P (m^3)	-	-	4.83	149.73	-
Time consumption					
t_{WP} (s)	-	-	-	4784	7.14
t_{M_OFF} (s)	-	-	-	7393	11.03
t_{M_ON} (s)	-	-	-	105	0.16
t_{CW} (s)	-	-	-	1300	1.94
t_{NC} (s)	-	-	-	2439	3.64
t_{TF} (s)	-	-	-	1436	2.14
t_{CSB} (s)	-	-	-	879	1.31
t_{DB} (s)	-	-	-	5561	8.29
t_{TB} (s)	-	-	-	3414	5.09
t_{BL} (s)	-	-	-	112	0.17
t_{RP} (s)	-	-	-	14,739	21.98
t_{TD} (s)	-	-	-	118	0.18
t_{M} (s)	-	-	-	14,759	22.00
t_{SD} (s)	-	-	-	4378	6.53
t_{WF} (s)	-	-	-	5635	8.40
t_{P} (s)	-	-	-	22,639	33.76
t_{NP} (s)	-	-	-	44,413	66.24
TST (s)	-	-	-	67,052	100.0
Fuel and lubricant consumption					
FM (L)	-	-	-	4.350	-
LO (L)	-	-	-	1.480	-
UFM ($L \cdot m^{-3}$)	-	-	0.029	-	-
ULO ($L \cdot m^{-3}$)	-	-	0.010	-	-
Performance metrics					
P_{NET} ($m^3 \cdot h^{-1}$)	-	-	23.81	-	-
P_{GROSS} ($m^3 \cdot h^{-1}$)	-	-	8.04	-	-
E_{NET} ($h \cdot m^{-3}$)	-	-	0.04	-	-
E_{GROSS} ($h \cdot m^{-3}$)	-	-	0.12	-	-

DBH: diameter at the breast height, DS: diameter at the stump height, P: production, FM: total fuel mixture consumption, LO: total lubrication oil consumption, UFM: unit fuel mixture consumption, ULO: unit lubrication oil consumption, P_{NET}: net productivity, P_{GROSS}: gross productivity, E_{NET}: net efficiency, E_{GROSS}: gross efficiency. "-" stands for not applicable.

This was the consequence of a great contribution of personal delays (21.98%) and time used to take the meal (22.00%), as well as the time used to travel forth and back to the accommodation place (15.54%). Delays caused by the study and by technical reasons only contributed 6.7% to the total study time and most of them consisted of refueling the chainsaw. In the productive time, the greatest contributor was the time spent on moving (33.29%), followed by tree debranching (24.69%), making the felling cuts (17.20%), and tree bucking (15.16%). Work tasks such as workplace clearing (5.77%) and leveling the stump and tree end (3.9%) contributed to a lesser extent.

The mean DBH was estimated at 67 cm, being close to that described by the utilization act (Table 1), while the mean diameter of the stump was 10-cm larger. Production was estimated at almost 150 m^3 based on the number of harvested trees during the study (31) and the average tree volume. Tree felling and processing of the 31 observed trees supposed a fuel mixture consumption of 4.350 l (0.029 $L \cdot m^{-3}$) and a lubricant consumption of 1.480 l (0.010 $L \cdot m^{-3}$), indicating a rather low amount of fuels consumed in operations.

In the observed conditions, the net and gross productivities were rated at 23.81 and 8.04 $m^3 \cdot h^{-1}$, respectively, with the gross productivity calculated by the inclusion of the total study time, meaning that the tree felling and processing of one cubic meter (net efficiency) took 0.04 hours when excluding different kinds of delays. However, under the real conditions of the study, the efficiency was 0.12 $h \cdot m^{-3}$. Given the fact that the worker observed in this study was paid on a daily basis, which probably also affected the way in which managed his working time, this figure characterizes the local conditions which take into consideration all the time taken into study. In fact, by excluding the meal time as well as the time used to get to the felling block and back to the resting place, as specific to the calculation of gross efficiency [38,44], the reported figure would have been smaller, standing for an improved gross efficiency.

3.2. Ergonomics of Motor-Manual Felling and Processing

3.2.1. Estimates of Workload

Table 4 shows a breakdown of the statistics and indicators that characterize the workload of the motor-manual worker. Assuming that a heart rate reserve greater than 40% characterizes a heavy job [42], all of the tasks characterizing the productive work time were rated as being difficult. From this point of view, struggling to release the blade of the chainsaw from the cuts, which was reported in this study as a technical delay, caused the highest physical strain to the worker (%HRR = 57.49), as this kind of task involves a substantial force exertion.

Table 4. Breakdown of the cardiovascular activity and of the experienced work difficulty.

Work Element	Time Spent (s)	Share (%)	Mean HR	St.dev. HR	%HRI	%HRR
WP	4784	7.14	93.5	±7.9	34	21.76
M_OFF	7393	11.03	118.0	±12.8	69	44.45
M_ON	105	0.16	116.9	±7.9	67	43.46
CW	1300	1.94	120.4	±14.3	72	46.66
NC	2439	3.64	121.5	±12.5	74	47.71
TF	1436	2.14	120.6	±13.3	72	46.90
CSB	879	1.31	126.6	±12.5	81	52.44
DB	5561	8.29	123.0	±14.4	76	49.12
TB	3414	5.09	114.2	±15.0	63	40.91
BL	112	0.17	123.1	±9.3	76	49.14
RP	14739	21.98	105.6	±14.9	51	33.10
TD	118	0.18	132.1	±9.0	89	57.49
M	14759	22.00	99.6	±9.4	42	27.39
SD	4378	6.53	102.8	±11.9	47	30.35
WF	5635	8.40	94.3	±12.4	35	22.53
TOTAL	67052	100.0	107.1	±16.0	53	34.38

Next in line was the task of levelling the stump and the tree end which was characterized by a heart rate reserve of 52.44%. Excepting tree bucking, all the tasks that were carried out in the felling block and made use of the chainsaw were characterized by a heart rate reserve higher than 45%. Even moving exceeded the difficulty threshold of 40%, indicating that all of those tasks carried out during the productive time were difficult. In this study, the difficulty of moving tasks could be attributed to the presence of a dense brush vegetation, since the terrain was flat. A heart rate reserve of less than 30% was only characteristic of events such as moving forth and back from the accommodation place to the felling block, as well as those of meal taking, in which there was some time for partial cardiovascular recovery. In contrast, during the rest pauses, the cardiovascular activity experienced by the worker exceeded the heart rate reserve threshold of 30%. According to [62] referenced in [20], high workloads are characterized by a percentage heart rate increase ranging from 78 to 114. From this point of view, only a minor share of the study time would be characterized by a high workload (1.49%). Nevertheless, there are references that indicate the fact that heart rates ranging from 110 to 150 bpm [63] cause a heavy stain for the worker and even heart rates in the range of 110–130 bpm constitute the upper limit for continuous work [64], placing all of the productive tasks of this study in these categories, as well as outside the acceptable limits (104 to 114 bpm) according to [65].

The heart rate reserve for the whole study time was estimated at 34.38%. However, it does not stand for the productive time and it incorporates all the data, including that recorded during the pauses, delays, meal time, and work preparation and finishing. A simple weighted calculation of the heart rate reserve for the productive time would lead to a value of about 46%, indicating a high physiological strain.

3.2.2. Exposure to Noise

During the study, the worker spent about 23% of the total study time in tasks that supposed the use of the chainsaw with the engine switched on, while about 67% of the productive time was spent with the chainsaw working, in different tasks. Table 5 shows a breakdown of the exposure to noise in different work tasks measured as the A-weighted sound pressure level calculated for each of the carried-on tasks, as well as for the total study time.

Table 5. Breakdown of duration and levels of exposure to noise by tasks and for the study.

Work Element	Time Spent (s)	Share (%)	LAeq	LAeq, Te	$L_{EX,8h}$
WP	4784	7.14	76.33		
M_OFF	7393	11.03	79.43		
M_ON	105	0.16	97.65		
CW	1300	1.94	100.36		
NC	2439	3.64	106.14		
TF	1436	2.14	105.35		
CSB	879	1.31	102.40		
DB	5561	8.29	101.53		
TB	3414	5.09	103.89		
BL	112	0.17	101.61		
RP	14,739	21.98	80.17		
TD	118	0.18	92.58		
M	14,759	22.00	75.65		
SD	4378	6.53	80.02		
WF	5635	8.40	78.05		
TOTAL	67,052	100.0	97.15	97.28	96.18

During the productive time, noise levels varied with the type of carried-on task. The greatest exposure to noise was recorded during the notch cutting (LAeq = 106.14 dB(A)) and making the felling cut (LAeq = 105.35 dB(A)), as in such work tasks, the feller was required to undertake work postures which generate shorter distances between the noise source and the ear. In addition, for most of the time spent on such tasks, the engine was operated near to its full capacity, therefore producing more noise compared to other tasks when the engine worked for much of the time in the idle state. Tree bucking supposed a substantial use of the chainsaw but also movements along the tree with the chainsaw operating in the idle mode, resulting in a mean exposure to noise of 103.89 dB(A). Clearing the workspace, levelling the stump and the tree end, debranching, and supplementary bucking at the landing accounted for similar noise exposures, ranging from 100.36 to 102.40 dB(A). Obviously, these levels of exposure were correlated with the chainsaw operation time which was low, excepting debranching tasks (8.29%). Anyway, the use of the chainsaw during debranching at the full capacity was lower compared, for instance, with the felling cuts. In addition, many of the tasks carried out with the chainsaw at the full capacity did not suppose the same distance conditions between the source of noise and the ear. Therefore, the exposure to noise in motor-manual tree felling and processing operations also depends on the work posture adopted by the worker, which is further related to the operational conditions, such as the tree diameter, knowing the fact that larger diameters involve more time to make the cuts.

The total daily exposure calculated for the whole study was 97.15 dB(A) and the mean total daily exposure for the study was 97.28 dB(A). Nevertheless, the observed work days did not account for exactly eight hours of work for each observation. The observed time varied widely, being 8.26 hours on the first day, 7.16 hours on the second day, and of 3.21 hours on the last day, hence the actual working time was, on average, of 6.21 hours per day. In addition, 15.54% of the study time was used to get to the job location and back to the rest place. Therefore, the calculated daily exposure for a nominal day ($L_{EX,8h}$ = 96.18 dB(A)), which also included the tasks of moving forth and back to the rest place, was 1 dB(A) lower than the actual daily exposure (LAeq = 97.15 dB(A)).

Compared to the European legislation and to the noise exposure assessment standards [49], the results of this study indicate that in most of the observed tasks, the exposure to noise exceeded the 80 dB(A) minimum action level. Only the travel to the work place and back (transport with the tractor used during the operations), movements with the engine switched off, and the meal pauses generated exposures to noise lower than this threshold. Such events, however, accounted for almost 50% of the observed time. On the other hand, 22.92% of the observed time was characterized by exposure to noise that well exceeded the exposure limit value set at 87 dB(A).

3.2.3. Postural Assessment

Table 6 shows an overview of the postural assessment broken down into the observed tasks in motor-manual tree felling and processing. The postural risk index of the observed tasks varied between 128.1 and 373.2, and, in general, it was higher for those tasks involving the operation of the chainsaw. In particular, notch cutting seemed to generate the highest postural risk index (373.2) of the observed operational tasks (Table 6), placing this kind of task close to action category 4.

Table 6. Postural risk index assessment of motor-manual tree felling and processing.

Work Element	Time Spent in the Study (s)	Share in the Total Study Time (s)	Frequency in the Postural Assessment Sample	Share in the Postural Assessment Sample (%)	PRI
M_OFF	7393	32.65	524	8.28	128.1
M_ON	105	0.46	8	0.13	137.5
CW	1300	5.74	611	9.65	264.5
NC	2439	10.77	1404	22.18	373.2
TF	1436	6.34	885	13.98	334.2
CSB	879	3.88	461	7.28	232.5
DB	5561	24.56	1711	27.03	215.3
TB	3414	15.08	622	9.83	296.9
TD	118	0.52	103	1.63	289.3
TOTAL	22645	100.00	6329	100.0	274.9

PRI: Postural Risk Index.

This situation is the result of the general body posture when making the notch as an effect of the local operational conditions, which were characterized by high diameters of the trees to be felled at the stump level (Table 3), a fact that required, in many cases, knee bending, as well as bending and twisting of the back, to be able to see how the cuts progressed into the tree. In general, making the felling cuts exceeded the postural risk index value of 300 and values closer to this threshold were recorded in the case of tree bucking, as well as in the case of those technical delays which supposed the actions needed to free the chainsaw's blade from the cuts. Except for those tasks which involved moving, tree debranching, and leveling of the stump and of the tree end, all of the calculated values of the postural risk index placed the tasks which require corrective actions to be taken as soon as possible near the threshold of 300 [60]. In such operational tasks, workers are required to undertake uncomfortable work postures (Figure 4), which in many cases, do not depend on the worker's strategy but on the local operational conditions. The global postural risk index which was calculated for the observed motor-manual tree felling and processing operations had a value of 274.9, being close to action category 3, which requires corrective actions as soon as possible [60].

(**a**) (**b**) (**c**) (**d**)

Figure 4. Awkward postures typical of motor-manual tree felling and processing: (**a**) Making the notch; (**b**) Making the felling cut; (**c**) Debranching; (**d**) Bucking.

Nevertheless, the frequency share of the tasks as observed in the postural assessment data set was different compared to the time study data set (Table 6). For instance, notch cutting accounted for more than 22% in the postural assessment study, while it accounted for a share of only 11% in the time study data set. Assuming that the postural risk index of each task would be the same irrespective of the time spent in each task would mean a much lower postural risk index (227.2), while this value would be even smaller when also considering those tasks which were not considered as being a part of the productive time. Nevertheless, in the ergonomic assessment of work postures, the productive time is that which makes the subject of analysis.

A more detailed analysis of the body segments (Figure 5) showed that in the motor-manual tree felling and processing operations, the main problem related to the risks of musculoskeletal disorders is that characterizing the posture of the back. As shown (Figure 5a), the frequency of postures described as having the back bent and twisted was very high, accounting for 67%. When such postures occur, irrespective of the arm and leg postures, the OWAS system classifies the whole-body posture in action categories ranging from 2 to 4. Coupled with leg postures characterized by knee bending (Figure 5c, codes 4 and 5), such situations always lead to the action category 4 according to the OWAS system. On the other hand, force exertion is difficult to estimate from pictures in motor-manual tree felling and processing. For this reason, force exertion was always attributed to less than 10 kg, based on reasons related to the chainsaw weight.

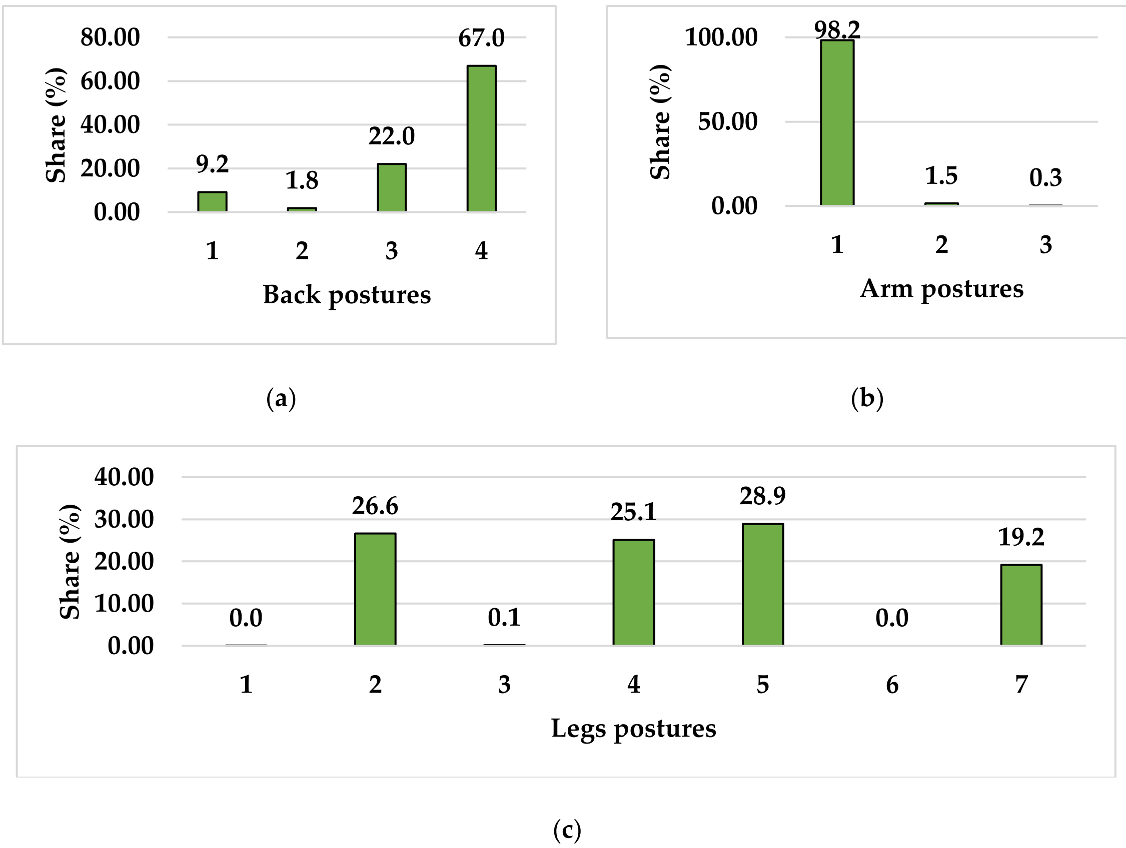

Figure 5. Shares of main body segment postures: (**a**) Back postures; (**b**) Arm postures; (**c**) Leg postures.

Assuming that the postural description of a given job requires a detailed analysis of those tasks which occur when the worker accomplishes his job, it thus only considers the time spent in operations. The conclusion that can be extracted from the postural assessment is that this kind of job has serious implications from the risk of musculoskeletal disorders standpoint. Furthermore, the case study described herein cannot describe all the variability that is typical of motor-manual forest operations [26], and therefore one could expect, for instance, even worse figures for similar operational conditions related to the tree size, in steep terrain.

4. Discussion

This study evaluated the ergonomic conditions of tree felling and processing in hybrid poplar clear-cuts. In such studies, a summary description of the operational conditions and productive performance helps in understanding the job tasks, physical strain, and exposure to harmful factors. There are many studies in the international literature that evaluated time consumption and productivity of motor-manual tree felling and processing and modeled them as a function of operational variables [11]. Productivity estimates from this study are generally in line with those reported by other case studies, which evaluated the productivity of tree felling when dealing with very large trees [18,66], following the general concepts of the "piece-volume law" [9]. In addition, the fuel and lubricant consumptions were rather low in this study, supporting similar facts reported in the scientific literature [67].

Heart rate is only considered to be a good predictor for cardiovascular activities in the range of 100–140 bpm [41], which was the case in this study. The workload experienced by the feller was found to exceed most of the acceptable thresholds existing in the available literature [42,63–65]. However, many factors could explain the physical workload experienced by the worker. For instance, in motor-manual tree felling and processing tasks, many parts of the job are undertaken by a significant contribution of the hand-work, while for the same job, the hand-work contributes to a greater extent to the heart rate behavior compared to the leg-work, also being a good indicator of the severity of muscular work [51]. Indeed, most of the productive time in this study was covered by hand-work and to a less extent by work tasks which involved a substantial use of the legs. There are hints that even small changes in work posture may cause significant changes in the heart rate response [68–70], which in this study, were difficult to accurately assess. However, those postures characterized by high risks of musculoskeletal disorders were also associated with most of the greatest heart rate reserves. While no significant relations could be found between the two, this points out the necessity to carry out detailed studies able to identify to what extent the work posture affects the physiological response of the workers. This was not possible in this study, as the collected postural data could not be exactly matched with the heart rate samples. One could expect the heart rate reserve during the rest pauses to come down to the resting heart rate but, in fact, it indicated a value even greater than those of work preparation and work finishing. The same was true for the meal pauses when the heart rate reserve was 27.39. This indicates the fact that even if taking rest pauses, which were significant in terms of time share in this study, the worker was not fully recovered. As a fact, depending on the exercise intensity, recovery may take up to 30 min [71].

Compared to other jobs [46,58,59], tree felling and processing is not characterized by a stationary work station, hence the exposure to noise depends to a great extent on the carried-on task and on the posture adopted by the worker, given the fact that distance to the noise source has an effect on the noise level [41]. Therefore, even for the same work task and for the same worker, one could expect variations as a result of the adopted work strategy. From this point of view, the distance between the source and the ear could be the effect of working posture, a fact that could be studied further to be able to think about redesigning the work. Even if not statistically evaluated, for those work tasks which were observed during the productive work time, there was a relation between the exposure to noise and the postural risk index (Tables 5 and 6), indicating a structural dependence between the two. What really matters is the fact that the thresholds set by the existing regulations [49] were exceeded in most of the observed tasks, as well as at the study level. This was also reflected by the exposure level normalized for an eight-hour day, facts which indicate that such jobs cannot be carried out without protective equipment. As an observation, the feller did not wear protective equipment against the noise, while only the use of ear plugs would have provided a sound attenuation between 15 dB for low frequency sounds and 35 dB for higher frequencies [41]. At the same time, modern helmets can provide a sound attenuation of 26 dB. Therefore, in conditions such as those observed in this study, any of this equipment would have reduced the exposure to an acceptable limit.

Comparisons to other forest operations studies may help in characterizing the job difficulty and exposure to harmful factors using the same parameters. In terms of heart rate increase, the results of this study were close, but different to those reported by [20] for felling and bucking operations. In their study however, the heart rate at rest was greater than that of this study. In terms of heart rate reserve, however, the results of this study indicated smaller workloads compared to [72] where the terrain slope was high (50–80%) and the work tasks shares in the study time were not mentioned, and close to those reported by [55] for the effective chainsaw work and for different delays. In choker setting tasks, heart rate reserve accounts for 36.4% [52] under conditions of steep terrain, in cable work it ranges between 21.6 and 76%, depending on the tasks and tools used [19,54], and cable rigging operations seem to put heavier strains on the workers with a heart rate reserve in the range of 67–80% [53]. Exposure to noise of motor-manual tree felling and processing, as reported in this study, was greater than that specific to skidding [58] and chipping operations [46,59]. In addition, the productive time in this study accounted for a small share of the total study time, hence, a greater utilization of the productive time would lead to increased exposure to noise and probably to heavier workloads and risks of musculoskeletal disorders. For instance, the postural risk index was estimated in this study to be 275, indicating a value which can be placed among the typical postural risk indexes reported for forestry work [27,28]. For instance, [27] reported that more than 50% of the posture frequencies of motor-manual tree-felling operations are attributed to third and fourth action categories. In other related jobs such as firewood processing [39] and wood debarking [47], the reported postural risk indexes were much lower compared to that from this study. As shown by this study, the main postural problems are those related to the back, which was found to be bent and twisted in 67% of the observations, as well as to the legs, which were found with knees bent in 54% of the observations. Such postures may lead to symptoms such as pain localized in the lower and upper back and knees, respectively, which seem to be the most frequent among the forest operations workers [24,25]. However, one could expect different results for different operational layouts, with increased postural risk indexes as the time spent in making the cuts of tree felling and processing increases. To be able to evaluate the postural risk indexes in such a wide range of operational conditions, automatic procedures and tools should be developed to ease the data processing and analysis effort.

5. Conclusions

The main conclusion of this study is that the motor-manual tree felling and processing of flatland poplar forests is heavy and hazardous work which loads the operators with heavy strains, exposes them to unacceptable noise levels, and generates increased risks of musculoskeletal disorders. In the short term, at least for Romania, it is impossible to change the harvesting technology of poplar stands to one characterized by an increased level of mechanization in tree felling and processing tasks. Therefore, all of the available knowledge, equipment, tools, and procedures that are proven to protect the workers should be used. In particular, rest pauses should be scientifically designed to ensure cardiovascular recovery, and to limit the exposure to noise during the operational time, protective equipment should be worn. At the same time, the results of this work should be interpreted as being indicative as they only account for a descriptive case study which can prove its utility and replicability in similar conditions. Nevertheless, variability induced by operational conditions, organizational layouts, and anthropometry of workers, as well as their general and operational behavior, should be documented in detail to be able to provide more conclusive results; questions that would require a significant research effort.

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