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RESEARCH ARTICLE

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Workload analysis in logging technology employing a processor aggregated with a farm tractor

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Abstract

Aim of study: The aim of this research was to analyze the workload of the operators while logging at the motor-manual level in coniferous stands undergoing two tending treatments (early and late thinning). The technologies under the investigation employed a power chainsaw, tractor equipped with a cable winch as well as delimbing and cross-cutting Hypro 450 processor.

Area of study, materials and methods: The research areas were located in lowlands and in a mountain range of the Western Carpathians. In the analysis it was assumed that the heart rate at work, expressed in beats per minute, would be an indicator of the workload affecting the human organism. Based on the heart rate, three indicators were calculated: relative heart rate at work (%HRR), 50% level of heart rate reserve, ratio of working heart rate to resting heart rate.

Main results: The lowest average workload (typical for light work, %HRR<20) was recorded for the processor operator in late thinning (%HRR=16), whereas, the highest one (indicating heavy work, %HRR=48.69>40%) was for the chainsaw operator in early thinning, working with a processor. Cumulative distribution function of the workload at the work station of the skidder operator was characterized by bimodality – an occurrence of two extreme, high and low, workload values.

Research highlights: The workload in early thinning was higher by about 7% than in late thinning at the work station of both, the processor operator as well as the chainsaw operator working with a processor.

Keywords: logging; tractor processor; heart rate; workload; cardiovascular strain.

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Introduction

Despite the rapid development of the multi-operational forestry machinery market, using such machines on a large scale in Polish forestry is mainly dependent on the investment capacities of forestry companies (Sowa *et al.,* 2007; Spinelli & Magagnotti, 2012). Market fluctuations and the considerable impact of the wood industry have caused a significant increase in the investment risk. Statistics for 2013 indicate (Anonymous, 2014) that the annual overall volume of wood harvested in Poland accounts for about 37 mil. m^3. In public forests (including properties of the State Treasury, communal units and National Parks) nearly 35 mil. m^3 of large wood (debarked stems of minimum diameter of 5 cm) is harvested. Solutions designed to decrease the weight of tools used for logging are limited and they usually involve skidding (Magagnotti & Spinelli, 2011; Ottaviani *et al.,* 2011). During the tending treatments performed in maturing stands (over the age of 20) – thinning – 16,990 thousand m^3 of large wood, including 10,592 thousand m^3 of large softwood, was harvested in Poland in 2013. It seems that a possible solution is mechanization appropriate for so-called small scale forestry (Spinelli & Magagnotti, 2012), including processors aggregated with farm tractors. It is estimated that the unit cost of such a solution would not exceed 6 EUR/m^3 (Sowa *et al.,* 2007). Delimbing and cross-cutting aggregates are mainly produced in Scandinavia, where their major manufacturers are located (Hypro AB, Melfare AB Lutea, Niab AS Fors MW, PATU).

Delimbing and cross-cutting processors are mounted on the three-point suspension system of a tractor. They are additionally equipped with a cable winch with a 2-ton pulling force (with a winch rope length of up to 50 m) and a hydraulic crane with a maximum radius of 6 m. These technical parameters allow the processing of stems up to 40 cm in diameter. Hypro and Melfare processors are furnished with movable rollers (similar to harvesters) providing the continuity of the delimbing process in contrast to cyclical delimbing systems applied in Niab and PATU processors. The possibility of controlling aggregates in two ways, from the tractor cab as well as at the processor panel in the standing position, eliminates the necessity to assume dangerous body positions while delimbing or cross-cutting and, so reduce the number of injuries and accidents at work (Grzywiński *et al.,* 2010; 2013).

However, before any new production solution is employed, an analysis that would indicate an improvement in work conditions should be carried out (Shannon *et al.,* 1998). It can be assumed that determining the cardiovascular load through monitoring heart activity is a universal indicator in this respect (Keytel *et al.,* 2005; Kim *et al.,* 2009). It is applied to examinations based on short-term observations (20 – 30 minutes) as well as lengthier ones lasting the whole day, or even an entire month, in the so-called diary method. A practical problem reported in many papers is a sure inconvenience resulting from the necessity to determine the power work capacity (Leonard, 2003). From the practical point of view, this activity is usually omitted when commencing analyses in the real environment with restricted access to workers is assumed (Kirk & Sullman, 2001; Magagnotti & Spinelli, 2011; Ottaviani *et al.,* 2011). The superior goal is to demonstrate the level of significant changes in ergonomic factors within the solution under the analysis. The variability in indicators is not only due to the technology and outer environmental factors (including the number of obstacles), it also results from motivation, engagement and temporary availability of the workers. Field research (Leszczyński, 2011) displayed that indicators of work heaviness explained a much smaller part of variances in the analyzed variables in comparison with the physicochemical parameters of the working environment or technology.

The aim of this research was to analyze the workload of the operators (expressed by relative heart rate at work) while logging at the motor-manual level in coniferous stands undergoing two tending treatments (early thinning and late thinning). The technologies under the investigation employed a power chainsaw, tractor equipped with a cable winch as well as delimbing and cross-cutting Hypro 450 processor. The research areas were located in lowlands and in a mountain range of the Western Carpathians.

Materials and methods

In the experiment the workload experienced by the fellers working with two technological variants of wood harvesting at the motor-manual level were compared. A) Long Wood System method (LWS): the chainsaw operator (CSO) performed cutting and delimbing with a power chainsaw, whereas, the farm tractor operator (TO) carried out semi-suspended skidding by means of a Fransgard 6000 cable winch mounted on the lift of a Zetor 6741 (74 kW) tractor. B) Cut-To-Length method (CTL) employing a Hypro 450 processor mounted on the lift of an MTZ 820 BELARUS (61 kW) tractor: the chainsaw operator (CSO&PO) only performed the cutting of trees, whereas, the processor operator (PO) carried out other processing operations, including hauling stems to the skidding roads by means of a cable winch mounted on the processor as well as delimbing and cross-cutting.

In the analysis it was assumed that the heart rate at work, expressed in beats per minute (BPM), would be an indicator of the workload affecting the human organism. Based on this value, three indicators characterizing the physical workload were calculated, as defined by Kirk & Sullman (2001):

(1) Relative heart rate at work using the formula of Vitalis,1987:
$\%HRR=(HR_{work}-HR_{rest})/(HR_{max}-HR_{rest})\cdot 100$, where HR_{work} – average working heart rate, HR_{rest} – resting heart rate, HR_{max} – maximum heart rate ($HR_{max} = 220$ – age of the study subject);
(2) 50% level of heart rate reserve using the formula of Lammert, 1972:
$50\%Level=HR_{rest}+0.5\cdot(HR_{max}-HR_{rest})$;
(3) Ratio of working heart rate to resting heart rate using the formula of Diament, 1968:
$Ratio=HR_{work}/HR_{rest}$.

The experiment was conducted in coniferous stands (pine, spruce and fir) during two cutting sequences of tending treatments (early thinning and late thinning). For every trial, three rectangular plots of 50x100 m^2 were established. The longer side was situated along an existing skidding road, which contributed to limiting the passage. In total, observations were carried out in 36 trial plots of an overall area of 18 hectares. As a result of the experiment 380 m^3 of wood was harvested, including 167 m^3 of wood extracted during early thinning treatments. The average breast height diameter (the stem diameter at the height of 1.3 m) was 18 cm in respect of early thinning (ET) and 30 cm in the case of late thinning (LT); the trees heights were respectively 17 and 22 m.

For recording the working times and workload Timing software was used. It was developed by a team from the Department of Forest and Wood Utilization, University of Agriculture in Krakow, and designed to be run on a minicomputer PSION-Workabout and Polar RS800 CX sports watch for monitoring heart rate. The Polar RS 800 CX sports watch consists of a chest belt with an in-built transmitter and two electrodes as well as a shoulder-worn device for storing data. The data was sent via radio waves from the transmitter to the receiver; the latter one resembled a shoulder-worn watch. The device performance is based on the principles of ECG measurement (Crawley, 2008) and the measurement error does not exceed 1% (www.polar.fi).

The resting heart rate (HR_{rest}) was estimated in 10-minute observation periods while the workers were sitting in the seat of the vehicles in which they had driven to the work station. In the research the principle of non-interference with the work process carried out by the people in the experimental area was assumed. Therefore, the observations were carried out in an unobtrusive manner. The values were read out only after the data had been transmitted to the computer, which eliminated the mental pressure exerted on the workers that might have occurred due to the urge to compete or improve the obtained results. Based on self-established procedure, the data collected by both of the devices was compared, without taking into account the preparatory and completing times. The observation time for a single trial plot was different and it oscillated between 4 and 6.5 working hours. Files with incidental breaks and stoppages were removed from the sets of data gathered. The research was conducted in the period of the greatest predisposition for physical exercise, i.e. between 8 am. and 2 pm.

In order to balance the experiment, a three-stage process of methodical sampling without replication was performed (Fisz, 1967). The sampling of 1,000 elements was carried out at the level of; a) a single experiment; b) three replications jointly; and c) three types of stands (pine, spruce and fir). As a result, the sets characterizing the workload in coniferous stands during two cultivation treatments (ET, LT) were obtained.

The experimental plots were located within an area of the Regional Directorates of the State Forests in Katowice and Kraków. The observations were conducted over a period of three years (2008-2010) by repeating experiments in early spring and early autumn by temperature from -3ºC to 12ºC. The logging operations were performed by a constant group of workers aged from 22 to 29 (Table 1). In fact, the workers engaged in the research were used to the piece wage system. To avoid problems resulting from maximization of the workload, as reported by i.a. Bünger *et al.,* (1997), Toupin *et al.,* (2007); Ottaviani *et al.,* (2011), for the time of the experiment the hourly wages system was adapted. The resting heart value was estimated in the so-called "sitting test".

The statistical analyses included descriptive characteristics of the sets as well as testing for homogeneity hypotheses using Pearson's chi-square test, equality of variances by means of Fischer-Snedecor F-test and equality of average values with the use of one- and two-sided t-test for data of unequal variances (heteroscedastic t-test). All operations on data and calculations were conducted using the VBA environment and procedures provided by Ms Office Excel 2007.

Results

Continuous time-motion analysis was performed, which allowed us to conduct analyses of the time structure and the technological operations duration. The acquired results indicated a high share of the operational time (sum of T1 and T2, Table 2) which varied from 71.3% for the processor operator in late thinning (PO_LT) up to 87.6% for the chainsaw operator in late thinning (CSO_LT, variant A). For comparing the time structures within the certain groups of technological operations, Pearson's test of homogeneity was applied. The results obtained (Table 3) when comparing pairs indicated statistically significant differences (p-value<0.01), even in respect of the very same operator.

Table 1. Characteristics of the workers that participated in the experiments

Variable	Age	Height, cm	Weght, kg	Body mass index (BMI), $kg \cdot m^{-2}$	Heart reate rest (HR_{rest}), bpm	Maximal heart rate (HR_{max}), bpm	50% Level
CSO	29	170	76	22.2	69	191	130
PO	22	182	76	26.2	72	198	135
TO	28	185	85	26.3	64	192	128

CSO - chainsaw operator; PO - processor operator ; TO - tractor operator

Table 2. Frequency of working times within the operational groups (n=1000) (in percent)

Variable	T1	T2	T4	T5	T7
PO_ET	61.6	25	1.8	6.60	5
PO_LT	44.6	26.7	4.3	20.30	4.1
CSO&PO_ET	28.9	53	5.6	11.10	1.4
CSO&PO_LT	41.5	44.5	2.2	9.60	2.2
CSO_LT	48.6	39	3.4	6.80	2.2
TO_LT	51.8	34.6	0	6.20	7.4

PO_ET - processor operator, early thinning; PO_LT- processor operator, late thinning; CSO&PO_ET - chainsaw operator by using processor technology, early thinning; CSO&PO_LT - chainsaw operator by using processor technology, late thinning; CSO_LT - chainsaw operator by means of skidding tractor technology, late thinning; TO_LT - skidding tractor operator, late thinning;
T1 - efective work time; T2 - auxiliary time; T4 - fault cleaning time; T5 - resting time; T7 - daily time for maintenance of supporting machinery.

Table 3. Pearson's chi-square test of the working time homogeneity

Variable		Chi^2-stat
PO_ET	PO_LT	108.6810**
CSO&PO_ET	CSO&PO_LT	47.6466**
CSO&PO_LT	CSO_LT	16.5696**
TO_LT	PO_LT	143.0509**
TO_LT	PO_ET	46.7024**

** - statistical significance at the level p-value < 0.01.
Abbreviations as in Table 2

When taking into account the workload during particular operations, the lowest value (excluding the tractor operator, in which case the time of fault removal was not identified, T4) was recorded at the work station of the processor operator in late thinning. The value of relative heart rate at work during a break (T5) accounted for %HRR=9.12, whereas, the respective overall heart rate was HR_{work}=76 bpm (Table 4). The highest load at the level of 56.98 %HRR (HR_{work}=l36 bpm) was observed for the chainsaw operator working in technology B (early thinning treatment). The occurrence of such a high value during maintenance (T7) can be explained by the worker behavior after a momentary peak load and delay in his heart response to the exercise.

The average values (Table 5) indicate that the lowest load was a characteristic trait for the work station of the processor operator in late thinning (PO_LT, %HRR=16, HR_{work}=85 bpm), whereas, the highest one was recorded for the chainsaw operator in early thinning, working in variant B (CSO&PO_ET, %HRR=48.69; HR_{work}=126 bpm).

In further statistical analyses the hypothesis of equality of variances for the samples obtained was tested. The Fisher-Snedecor test conducted (Table 6), contradicted this hypothesis at the level p-value<0.00l, displaying diversity in the workload experienced by the fellers at the investigated work stations. In order to confirm the differences in aver-

Table 4. Characteristics of the workload per specified working times

	variable	PO_ET	PO_LT	CSO&PO_ET	CSO&PO_LT	CSO_LT	TO_LT
T1	HR. bpm	90	85	125	119	114	98
	%HRR	19.05	15.91	48.14	43.20	39.05	25.05
T2	HR. bpm	107	92	133	120	116	94
	%HRR	31.93	20.75	54.39	44.42	41.09	22.01
T4	HR. bpm	106	89	102	91	92	0
	%HRR	31.63	19.02	29.77	20.90	22.40	0.00
T5	HR. bpm	89	76	104	101	100	82
	%HRR	18.57	9.12	31.35	29.27	28.20	12.51
T7	HR. bpm	100	87	136	101	106	88
	%HRR	26.70	16.86	56.98	29.35	33.39	17.19

Abbreviations as in Table 2.

Table 5. Descriptive statistics of the workload (n=1000)

Variable	Mean HR, bpm	SD HR, bpm	Mean %HRR	SD %HRR
PO_ET	95	17.8	22.85	13.29
PO_LT	85	13.7	16.00	10.20
CSO&PO_ET	126	19.7	48.69	15.53
CSO&PO_LT	117	17.2	41.61	13.57
CSO_LT	113	14.7	38.42	11.56
TO_LT	95	19.4	22.64	15.36

Abbreviations as in Table 2.

Table 6. Results of hypothesis tests for the relative heart rate at work, %HRR

Variable 1	Variable 2	F-statistics	HA[1)]	t-statistics	Delta[2)]
PO_ET	PO_LT	1.6991***	H1>H2	12.9234***	6.85
CSO&PO_ET	CSO&PO_LT	1.3099***	H1>H2	10.8530***	7.08
CSO&PO_LT	CSO_LT	1.3788***	H1>H2	5.6624***	3.19
TO_LT	PO_LT	2.2690***	H1>H2	11.3922***	6.64
PO_ET	TO_LT	0.7488***	H1=H2	0.3184[ns]	0.20

*** - statistical significance at the level p-value<0.001; ns - no significance (p-value=0.7502); 1) HA - alternative hypothesis; 2) delta - %HRR average differences between variable 1 and variable 2. Abbreviations as in Table 2.

age value of the workload expressed in %HRR, the t-test for samples of unequal variances was applied (heteroscedastic t- test). The results presented in table 6 indicate that the workload in early thinning was by about 7% higher than in late thinning at both work stations, of the processor operator and the chainsaw operator working in variant B. A statistically significant increase in the workload was also observed in the case of the chainsaw operator working in technology B (with a processor) when compared with individual work (technology A); the detected difference accounts for 3.19 %HRR. Having analyzed a graphical presentation of the distribution of %HRR variable displayed in figures 1 and 2, bimodality of the workload of the skidder operator appears to be an interesting observation (Figure 2). The occurrence of extreme, high and low, values of the workload experienced by the operator appears to be a distinctive trait for this particular work station.

From the practical point of view, we often estimate the limit values of the workload, which, according to Strasser (Stampfer *et al.,* 2009), are in fact individual values. Nevertheless, we frequently assume, according to Bullinger (Ottaviani *et al.,* 2011), the limit value %HRR=40 of the so-called maximum heart rate reserve as well. A value exceeding beyond the limit value while working in the trial areas may

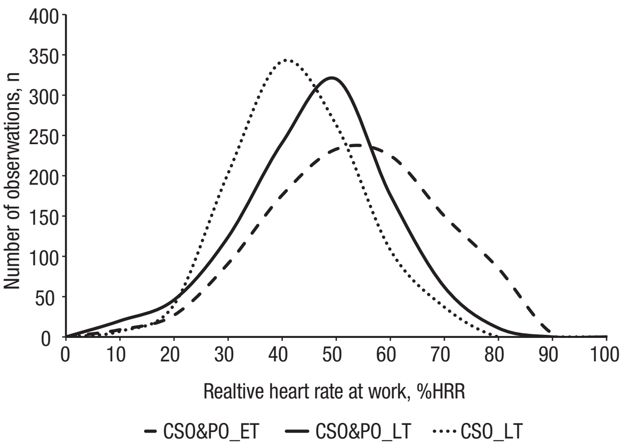

Figure 1. % HRR probability distribution functions for the chainsaw operator.

be presented by means of a cumulative probability. The analysis of the curves displayed in figures 3 and 4 indicated that the lowest probability of working above the specified threshold, i.e. constant capacity of the human organism, was recorded while operating a processor in late thinning (0.013, Figure 4), whereas, the highest one was observed in the case of the chainsaw operator working in the variant with a processor in early thinning (0.697, Figure 3).

Figure 2. %HRR probability distribution functions for the processor operator and skidder operator.

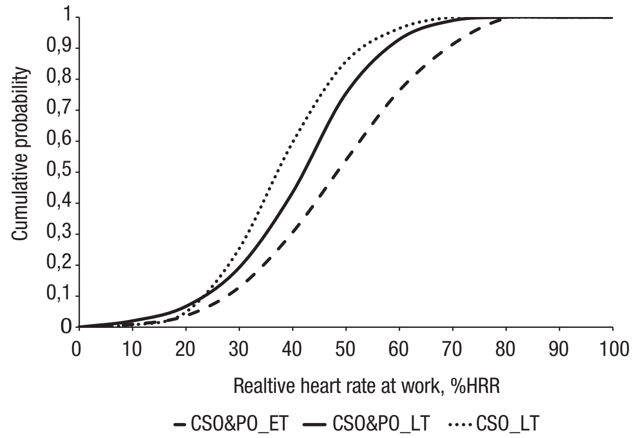

Figure 3. Cumulative %HRR probability for the chainsaw operator.

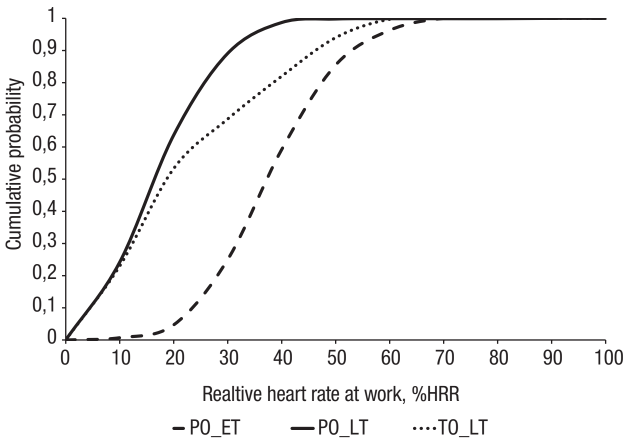

Figure 4. Cumulative %HRR probability for the processor operator and skidder operator.

Discussion

The physical workload may be characterized by many parameters described in this paper. It may be expressed in units of energy, number of heart beats at work (net cardio cost), percentage of utilized heart rate reserves (%HRR), 50% Lammert indicator, ratio between the heart rate at work and the resting heart rate (Kirk & Sullman, 2001). Due to the strong relation between the heart rate at work and the oxygen absorbed (V_{O2}), the indicator of heart rate reserves utilization (%HRR) is preferable.

The volume of oxygen absorbed against the maximum value (V_{O2max}) is the basic criterion in classification of the workload. Exceeding the threshold of 50% in individual values shows an extremely heavy workload involving an anaerobic energy release (Fibiger, 1978), which consequently leads to so-called oxygen debt. By analogy, the threshold %HRR=40 is considered as the limit value of the so-called constant capacity of the human organism (Stampfer *et al.,* 2009). Schlick *et al.,* (2010) pointed out that the limit value should account for NCC=40 bpm at work if the resting value (HR_{rest}) was estimated for the lying down position. Otherwise, it was suggested to decrease this value to 35 bpm. Having inserted the last-mentioned value into formula 1, the permissible %HRR threshold was obtained, which oscillated between 27 for the skidder operator and 29 for the chainsaw operator, thus, it was much lower than the one used in the results analysis.

Having employed the data displayed in tables 5 and 1, the net cardiovascular cost (NCC) could have been estimated directly, the value of which regarding the chainsaw operator oscillated between 44 and 57 bpm. Assuming the lower threshold value (a stricter criterion), it may be stated that in all the analyzed variants of the chainsaw operator work, the threshold of so-called constant capacity was exceeded.

The ratio of the heart rate at work to the value of 50% Lammert level (HR_{work}/50%Level) is another indicator of the workload. The results displayed in table 5 are below value 1. This indicates that the workers avoided exceeding a certain threshold of physical load. The result obtained indirectly confirms the “Constant Strain Behavior” analyzed in detail by Toupin *et al.,* (2007). However, it should be noted that in the case of short-term observations the workers may tend to exploit the full load of their organisms (Ottaviani *et al.,* 2011), which may significantly affect, if not prevent us from, conducting any analysis of the obtained results.

Based on the published data quoted in the paper (Kirk & Sullman, 2001), the values of the ratio of working heart rate to resting heart rate exceeding 1.45 allow us to rank the work of the chainsaw operator and skidder operator as heavier than nursing and car assembly work. The workload of the processor operator is comparable with that of steel workers, in which case the value of HR_{work}/HR_{rest}=l.28 is assumed. On the other hand, the workload of the chainsaw operator in early thinning (variant B) may be compared with that of a cable hauler choker setter working in mountainous terrain – (HR_{work}/HR_{rest}=1.84).

The workload analysis is an individualized research tool and it often depends on the temporary predispositions of workers. Taking into consideration the existence of the circadian cycle, the research presented herein was conducted in the periods of the highest predisposition for physical exercise. It seems that the assumed time for conducting the research results in extremely high coefficients of the operational time usage (Table 2). However, many publications report that the number of breaks (overt and covert ones) during heavy physical work may account for as much as 40% (Sowa *et al.,* 2006; Leszczyński & Jałowska, 2011).

Summary and conclusion

In the experiment the workload experienced by an operator of a skidder equipped with a cable winch, an operator of Hypro 450 processor aggregated with a farm tractor and a chainsaw operator working in two variants (A – individual work, B – cooperation with the processor operator) were compared. For the analysis a few indicators that characterize the workload were employed. Due to the strong relation between the heart rate at work and volume of absorbed oxygen (V_{O2}), it was assumed that the heart rate reserve utilization %HRR would be the most significant indicator.

Pearson's test for homogeneity of comparison in pairs was used to demonstrated the statistically significant differences in the working day structure, even in respect of the very same worker. The lowest average workload (typical for light work, %HRR<20) was recorded at the work station of the processor operator in late thinning (PO_LT, %HRR=16, HR_{work}=85 bpm). The highest workload, indicating heavy work, (%HRR>40) was observed for the chainsaw operator in early thinning, working in variant B (CSOSPO_ET, %HRR=48.69, HR_{work}=126 bpm).

It was established that the workload in early thinning was higher by about 7% at both the work stations of the processor operator and the chainsaw operator working in variant B. A statistically significant increase in the workload of 3.19 %HRR was also noted for the chainsaw operator working in technology B (with a processor) in comparison with the individual work (technology A). The differences observed in the workload at lower work efficiency seem to be useful in the context of introducing changes in remuneration systems in forestry work proposed by Toupin *et al.,* (2007). At the work station of the skidder operator bimodal distribution of the workload values was recorded (an occurrence of extreme, high and low).

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