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ORIGINAL RESEARCH ARTICLE

Comparing methods of energy expenditure estimation using forestry as an example

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Abstract. In this paper the values of energy expenditure obtained with estimative methods (tables of energy expenditure, Lehmann's method) were compared to the data obtained with a method based on pulmonary ventilation measurements. Thereby, the usefulness of estimative methods for determining energy expenditure on work stations in forestry was tested.

We compared energy expenditures for 30 forestry workstations within which 59 different activities were distinguished. For each activity the energy expenditure was determined utilizing the three following methods: pulmonary ventilation measurement, tables of energy expenditure and Lehmann's method.

The percentage error in energy expenditure for particular activities determined with tables ranged from -44.47% to 42.31%. The highest representation of error value (52.8%) varied between -19.9% and 5.0%. The error in energy expenditure estimation determined with Lehmann's method is characterised by a smaller variability ranging from -31.35% to 34.13%. The highest density of error values was found in the range from -4.9% to 10.0%, which comprises 44.1% of the results. To conclude, the use of tables resulted in an underestimation of the energy expenditure value for 64.1% of activities, whereas the use of Lehmann's method resulted in an underestimation in 49.1% of the cases.

Key words: energy expenditure, comparison of methods, forestry

1. Introduction

The energy expenditure (EE) of work is a value used to assess physical workload. The gasometric method (indirect calorimetry), based on the volume of oxygen consumption, is commonly used for this purpose. It is a reliable method; however, it requires the use of specialised measuring instruments. A simplified version of the calorimetric method is often used in industry to measure EE, namely by measuring lung ventilation – the volume of air inhaled or exhaled (Koradecka, Bugajska 1998).

In situations where taking measurements is not possible, estimation methods, such as EE tables and Lehmann's method, can be applied to determine EE. In both methods, a time study of the work day needs to be taken to determine the proportion of individual work activities to estimate the energy load of a work shift.

The tabular method uses research results on EE values from the literature published thus far. Sets of EE in forestry are found in the work of Jakubowski (1973), Fibiger (1976), Fibiger and Rogoziński (1977), Józefaciuk and Nowacka (1993) and Grzywiński (2007), among others. When using tables, one must remember that significant differences may arise due to, among others, technological advances, work pace, the size of transported loads, work organisation, site and weather conditions, etc.

The unit of EE for specific activities is determined in two stages with Lehmann's method. The first stage is an assessment of the body's position during work. The EE for maintaining that position is determined from tables.

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The second stage is an assessment of the main muscle groups involved in performing work activities and the intensity of the effort. Then, using another table, the EE associated with performing a given activity is determined. The net energy cost of the work is the sum of the results obtained from both stages (Lehmann 1966). It should be remembered that the tables relate to the energy costs of working men. For women, the table value should be multiplied by a factor of 0.80–0.85. A modified Lehmann's method is used to determine the metabolic rate associated with body position, type of work and movement of the body, related to the intensity of the work performed (PN-EN ISO 8996:2005).

According to various authors, the use of estimation methods allows the EE to be specified with an accuracy of approximately 10–20% (Konarska 1985; Koradecka, Sawicka 1987; Rogoziński, 1988; Pałka 1990; Dębowski, Spioch 1992). In their analysis of several activities related to timber harvesting, Sowa and Kulak (1999) found large error values when calculating estimated EEs, reaching almost 74%. According to the authors, much larger errors are incurred using the tabular method than Lehmann's method, resulting in an overestimation of EE for specific activities and significantly changing the picture obtained of a daily workload by aggregating the EE values for subsequent activities performed at the workstation.

The aim of this study was to compare simple methods to estimate EE with data obtained from pulmonary ventilation measurements and to assess the usefulness of estimation methods to determine the energy load for workstations in forestry.

2. Study methods

Comparisons of EE amounts were performed for 30 types of forestry work representing the basic tasks of forest management (silviculture, conservation and utilisation). Fifty-nine activities were distinguished in the analysed tasks, for which the EE value was determined by three methods: measurement – pulmonary ventilation measurements (using the MWE-1 EE meter), sets of tables, and Lehmann's method.

When analysing the results, the baseline EE value was the measurement obtained from pulmonary ventilation results using the MWE-1 EE meter. This measure is based on the existence of an almost linear relationship between the amount of oxygen consumed during exercise and the magnitude of lung ventilation in 1 min (Kozłowski, Nazar 1999). The measurement of pulmonary ventilation and EE was carried out according to the methodology recommended in the literature (Koradecka, Bugajska 1998; Makowiec-Dąbrowska et al., 2000).

The secondary percent error (P_{we}) was calculated for the EE amount obtained from Lehmann's method and the sets of tables according to the formula (Sowa, Kulak 1999):

$$P_{we} = \frac{WE_{LT} - WE_P}{WE_P} \times 100\%$$

where $WE_{L/T}$ is the EE determined by using Lehmann's method or the set of tables, and WE_P the EE determined by direct measurement methods.

3. Study results

Error in determining the EE of work activities

The secondary percent error when using the tables to determine the EE for individual activities ranged from -44.47% to 42.31% (Fig. 1). The error assessment of EE values obtained with Lehmann's method was less variable – from -31.35% to 34.13%. The difference in the mean percent error values of the analysed methods differed significantly ($p = 0.048$).

The largest representation of the error value (52.8%) was in the range of -19.9% to 5.0%. The highest density of values was found for the range of -4.9% to 10.0%, which represents 44.1% of the results (Fig. 1). The use of tabular sets resulted in lowered values of EE for 64.1% of the work activities, whereas with Lehmann's method, for 49.1% of activities.

Error in determining the energy expenditure of a work shift

Table 1 presents the EE secondary percent error values for a work day (8 h) obtained using the tabular and Lehmann's methods. The secondary percent error values of EE estimates for a work shift using the sets of tables ranged from -33.31% to 33.31%. The range of values for Lehmann's method was smaller, from -17.67% to 26.31%. The tabular method led to underestimating (x = -7.43%) the EE values of a shift ($p = 0.014$), while Lehmann's method resulted in a slight overestimate ($x = 2.35\%$). The tabular method resulted in underestimating the amount of EE for 56.0% of the work activities and for 46.7% of the activities with Lehmann's method.

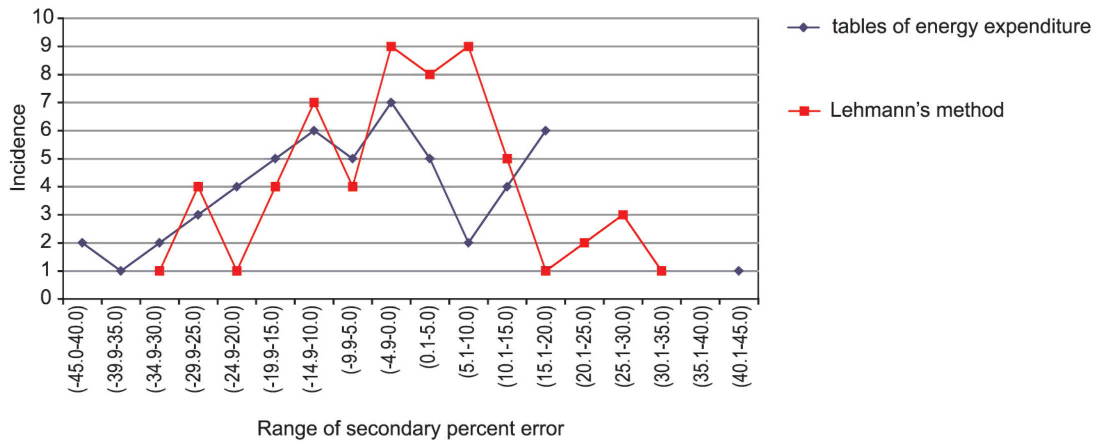

Figure 1. Graph of the density function of the secondary percent error (%) for the applied methods of estimating EE.

Table 1. Secondary percent error [%] of net energy expenditure for a work shift determined by the applied methods

Workstation or type of work		Energy expenditure tables (%)	Lehmann's method (%)
Planting with a standard dibble:			
	Planter	1.09	8.23
	Helper	-22.49	26.11
Planting with a Getinga dibble:			
	Planter	14.10	22.38
	Helper	-22.70	26.31
Planting with a Huffa dibble:			
	Planter	33.31	20.84
	Helper	-22.40	25.00
Manual soil scarification		-8.02	4.44
Planting with a spade:			
	Planter	6.09	6.21
	Helper	-22.80	7.01
Manual weeding with a scythe		5.69	-1.40
Motor-manual weeding		-	-7.15
Early cleaning with a machete		10.41	3.18
Enclosing a forest plantation:			
	Main worker	-	-3.19
	Helper	-	-16.22
Treating stumps with PgIBL		-	-3.74
Hanging bird boxes		-	-7.46
Late cleaning with a chainsaw		4.20	0.99
Early thinning / motor-manual technology:			
	Feller	-10.65	-5.78
	Feller's assistant	-14.00	-1.14
	Skidder-driver of an Ursus C-330 agricultural tractor	-27.55	5.61

Workstation or type of work		Energy expenditure tables (%)	Lehmann's method (%)
Late thinning / motor-manual technology:			
	Feller	-8.58	-3.21
	Feller's assistant	-7.99	1.37
	LKT-81skidder-driver	-8.78	-7.03
	Horse-drawn skidder (carter)	-28.68	-1.82
Late thinning / full-machine technology:			
	Harvester operator	5.13	4.54
	Forwarder operator	-33.31	-17.67
Late thinning / full-machine technology with a mid-field:			
	Harvester operator	4.59	4.14
	Forwarder operator	-32.03	-17.30
	Feller	-2.02	2.07
	Feller's assistant	1.60	-4.91

4. Discussion

The study indicates that estimating the EE of individual work activities may result in secondary percent errors in the range of -44% to 42% when using tables and from -31% to 34% with Lehmann's method. For most of the work activities, using tables, resulted in underestimates of about -20%, while Lehmann's method caused a slight underestimation (up to -5%) in most cases or an increase (to 10%) of EE values compared with pulmonary ventilation measurements. It was found that differences in the EE of specific activities were partially eliminated and the secondary percent error value of EE for work shifts was reduced.

Such significant differences in the EE level between values obtained from pulmonary ventilation measurements and those estimated from the tables may be due to incomplete information on expenditures in the literature and because they originate from a period of several decades. The EE value was estimated for some activities from data for similar, but not identical, activities, which may have led to larger errors. In addition, the values provided in the literature are not uniform – they are presented as net or gross EE (with basal metabolic rate), for standardised persons, lacking parameters for height, weight or body mass, with no information about the pace of work and the microclimatic conditions. Differences may also arise from the specific nature of the work in various branches of industry and the technological changes that have occurred (Koradecka, Bugajska, 1998; Makowiec-Dąbrowska et al., 1994, 2000).

In the case of Lehmann's method, the greatest source of error may be the incorrect classification of the muscle groups involved in performing the activities and an erroneous determination of the intensity of the effort. The error rate may also be significantly impacted by the pace of the work (Makowiec-Dąbrowska, 1988; Makowiec-Dąbrowska et al., 2000).

Using sets of tables from the literature to determine EE levels results in an underestimate of both individual work activities, as well as of an entire working day. Lehmann's method provides greater accuracy, which would favour its use when EE measurements cannot be taken. This method can still be used to assess EE in the workplace to make improvements, assess metabolism to determine microclimatic norms or verify the guidelines for providing high-energy meals. In terms of its use to determine whether high energy meals are needed, the possibility of error at a level of 20% should be remembered. For this reason, the energy load should be measured directly when borderline results are obtained.

5. Conclusions

The following conclusions can be drawn based on the study performed:

The method of using sets of EE tables underestimates the results of EE required for individual work activities.

Using Lehmann's method results in a lower level of error in determining the EE for a workstation.

We found that the differences in EE for specific work activities were partially eliminated and the secondary percent error for the EE of a work shift was reduced when both estimating methods were used.

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Author's contribution

W.G. gave research idea, literature review, data collection and analysis, supervision of manuscript preparation. P.M.S. performed the study and data collection. M.B. performed the study and data collection.