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The aim of this study was to validate the Edholm scale (Edholm, 1966) and the ISO 8996 standard (International Organization for Standardization [ISO], 1990) by comparing the metabolic rates estimated for both methods with the actual measured metabolic rate (M_{Meas}) in 6 manual material handling tasks simulated under laboratory conditions. The metabolic rate was calculated from oxygen consumption $\dot{V}O_2$ (19 participants) according to Standard No. ISO 8996 (ISO, 1990). Additionally, the participants estimated perceived exertion using the Borg scale. The metabolic rates derived from the Edholm scale (M_{Edh}) overestimated 5 of 6 activities by 34–50% (α = .05). The metabolic rates derived from ISO 8996 (M_{ISO}) overestimated all activities by 7–38% (α = .05).

energy expenditure   heat production   light and moderate work
manual tasks   heart rate   RPE

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1. INTRODUCTION

In many ergonomic studies, the evaluation of worker's energy expenditure is required. Knowledge of the metabolic rate is required, for example, in the assessment of working practices, energy cost of specific jobs or sport activities, and the total energy cost of an activity (Standard No. ISO 8996; International Organization for Standardization [ISO], 1990). Determination of metabolic rate becomes a crucial task in the investigation of the thermal working environment as the metabolic rate (and thus the endogenous heat production) is a determinant variable for thermal comfort and thermal strain (Horwat, Meyer, & Malchaire, 1988).

The direct measurement of oxygen consumption provides the most accurate estimate of metabolic heat production (Standard No. ISO 8996, ISO, 1990). However, it is difficult to measure oxygen uptake in the field, as measuring equipment is usually expensive, and sometimes it is impossible to measure oxygen consumption due to working conditions (e.g., during mast work). Furthermore, measurements significantly interfere with work performance, which leads to biased results (Horwat et al., 1988). The direct measurement of oxygen consumption in the field has to be limited to selected working periods (because of discomfort it can hardly be extended beyond 30 min), which are then considered as representative of the whole task. This work sampling procedure may be a source of error in work load evaluation over the whole working shift (Malchaire, Wallemacq, Rogowsky, & Vanderputten, 1984). These limitations make other, simpler, metabolic rate evaluation methods more practical for field measurements.

Other methods to assess heat production are direct and indirect calorimetry methods (these require a rather large number of different measurements) and simpler indirect methods based on heart-rate measurements (Nielsen & Meyer, 1987), pulmonary ventilation (Datta & Ramanathan, 1969; Ford & Hellerstein, 1959), cardiac output (Muzi et al., 1985), surface electromyography of the main muscles (Bobet & Norman, 1982), or acceleration measurement (Montoye et al., 1983). Most of these methods present drawbacks as far as equipment and work interference are concerned, or are likely to be appropriate only for specific types of activities (Horwat et al., 1988). The most common of the indirect methods are observations of physical activities (Edholm, 1966; Standard No. ISO 8996, ISO, 1990) or estimations of perceived exertion by the worker himself (Borg, 1970).

One observational method proposed by Horwat et al. (1988) divides the work done into elementary tasks, postural activity and displacement, taking into consideration their sequence and duration. By using tables such as those proposed by Standard No. ISO 8996 (ISO, 1990), the metabolic rate of each of these elementary activities can be determined and the energy expenditure of the whole period estimated by summing the energy costs of elementary activities over the period of time. The Edholm scale (Edholm, 1966) assesses metabolic rate based on the recordings of occupational activities and the duration of those activities (Kähkönen et al., 1992).

Ilmarinen, Knauth, Klimmer, and Rutenfranz (1979) reported that the metabolic rates were overestimated for occupational activities in six branches of industry with no heavy physical work that belongs to the categories "Sitting or standing with very light movements or activities" and "Activities with low intensity" of the Edholm classification (Edholm, 1966) system. The metabolic rates of the "producing information" groups that are classified in the same categories tended to be overestimated as well.

Methods based on the observation of worker's activities do not interfere with the work procedure, but require well-trained observers. A study by Kähkönen et al. (1992) revealed that the metabolic rate derived from the Edholm scale (Edholm, 1966) was higher than that from the Standard No. ISO 7243 (ISO, 1989) tables with differences between individual observers of tens of W/m^2 and in some cases over 100 W/m^2. Furthermore, the differences in the estimations of metabolic rate between the observers were sometimes up to 60%.

The study by Ilmarinen et al. (1979) validated the Edholm scale (Edholm, 1966) under field conditions. This study aimed to validate the Edholm scale (Edholm, 1966) and the Standard No. ISO 8996 (ISO, 1990) tables under laboratory conditions. It was designed to compare the measured metabolic rate under laboratory conditions during different manual tasks with the metabolic rate estimated by two methods: the Edholm scale (Edholm, 1966) and Standard No. ISO 8996 (ISO, 1990).

2. METHODS

2.1. Participants

Nineteen (14 males, 5 females) healthy participants volunteered to take part in the experiment. Before the experiment, the participants were informed of the details of the experimental procedures and the associated risks and discomforts. The participants' mean age was 29.0, *SD* 5.4 years, average body mass 69.2 kg, *SD* 12.7 kg, average height 1.72 m, *SD* 0.09 m and average estimated body surface (DuBois area) 1.81 m^2, *SD* 0.17 m^2. The participants were asked to abstain from strenuous physical activity on the morning of the measurement in order to minimise residual effects on the metabolic rate measurements.

2.2. Measurements

The study was limited to involve activities of low ($65 < M \leq 130$ W/m^2) and moderate ($130 < M \leq 200$ W/m^2) metabolic rate (Standard No. ISO 8996, ISO, 1990). Six manual material handling tasks occurring in normal work were designed under laboratory conditions (Table 1). A metabolic rate value (M_{Edh}) for each of the activities was derived from the Edholm scale (Edholm, 1966). Metabolic rates M_{ISO} were derived from the Standard No. ISO 8996 (ISO, 1990) tables. The participants performed the tasks in a random sequence. As the metabolic rate shows diurnal fluctuations, the measurements were always conducted in the morning (8.30–13.00) under thermoneutral conditions (ambient temperature 22.1–22.4 °C).

Oxygen consumption ($\dot{V}O_2$) was measured with a MetaMax® Metabolic Testsystem (Cortex Biophysik GmbH, Germany). It consisted of a base unit (gas analyses), a moistening Nafion® tube (to guarantee constant humidity during the measurement), a facemask with a head cap assembly together with a Triple-V® volume transducer. Fahlgren, Wiktorin, and Bernmark (1997) reported that oxygen consumption measurements conducted with MetaMax® were reliable and that the measured values agreed with values measured with the Douglas bag technique. The correlation coefficient between values measured with MetaMax® and the Douglas bag was .99.

Participants were accustomed to the apparatus before measurements were made. The morning resting metabolic rate (M_{Rest}) at normal room temperature was measured to obtain a reference point in the study before measuring metabolic rates when participants were performing various tasks. Participants took their latest meal at least 2 hrs before the experiment began, and were at rest (lying for at least 10 min) while measuring M_{Rest}. Oxygen consumption ($\dot{V}O_2$) was measured every 10 s continuously during the whole time of the experiment without participants taking off the facemask. Every time a participant exhaled the pump in the base unit started working in proportion to the respiratory flow. The exhaled air was collected in a mixing chamber. O_2 and CO_2 sensors took samples of the exhaled air

TABLE 1. Tasks Performed by Participants

Task Code	Body Posture	Type of Work	Work Activity	Description of the Activity
1	Sitting	Hand work: light	Sitting and typing	A participant is typing an extract of a novel written in English, using keyboard and mouse. Both hands are involved in typing.
2	Sitting	Two-arm work: light	Sitting and performing light assembly line work on a particle board that is placed on a horizontal working surface	A participant reaches for a bolt and a nut that need to be fastened together on a particle board. He/she takes and screws them together on the particle board that is in front of him/her. After all pairs are screwed together, the participant unscrews them and places the pieces in the original place. All the work is done on the same working surface.
3	Sitting	Two-arm work: average	Sitting and moving loads over a horizontal distance on the same working surface while employing both arms	A participant grips a load that weighs 1 kg, on a horizontal working surface, and moves it over a distance on the same working surface. The distance (0.45–0.65 m) over which the load is moved is adjusted to the anthropometric characteristics of the participant, so that no trunk work is involved. The experimenter paces the task at a rate of 30 times per minute.
4	Standing	Hand work: light	Standing and searching for information in a dictionary	A participant is given a list of English words that need to be found in an English-Swedish language dictionary. The participant writes down the first given translation into Swedish of the English word. Both hands are involved while turning the pages of the dictionary.
5	Standing	One-arm work: light	Standing and moving loads upwards from a lower working surface to an upper working surface and downwards from an upper to a lower working surface	A participant grips a 0.37-kg load from a shelf at his or her shoulder level and places it on a shelf that is 27 cm above the original shelf. After all 10 loads have been put on the upper shelf, the participant performs a reverse action by putting them down. The participant is free to choose the arm to be employed in the working activity. The experimenter paces the task at a rate of 30 times per minute.
6	Standing	Two-arm work: average	Average assembly line work employing two arms on a horizontal working surface that is 0.73 m from the floor	A participant reaches for a cross-head screw to be screwed into a wooden board. The work is done on a horizontal working surface at 0.73 m from the floor. Bending is needed to reach the working surface. The experimenter paces the work at a rate of 2 screws per minute.

continuously and measured it twice a second. Parallel recordings of heart rate were made with a Polar® PE 3000 heart rate monitor (Polar Electro Oy, Finland) at 10 s intervals. Measured metabolic rate (M_{Meas}) was calculated from the O_2 consumption using the partial method of measurement that is described in Standard No. ISO 8996 (ISO, 1990), which is recommended for the case of light and moderately heavy work.

After the participant's M_{Rest} had been measured, the participant started to perform simulated work tasks. Each participant was assigned one random task after another until all six simulated tasks were performed. The preliminary period of 3–4 min for each new activity was followed by a main period of another 3–4 min of work. In addition, subjective estimates of exertion were obtained using the RPE scale (Borg, 1970). Before the experiment began, the participants were instructed how to rate the degree of exertion. They were asked to rate it as accurately and naively as possible. After a particular activity was completed the participant was immediately asked to mark a number on a scale according to how the work was experienced. The interpretation of M_{Meas} can be found in Standard No. ISO 8996 (ISO, 1990) and the Borg scale (RPE) is described in Borg's study (Borg, 1970).

3. DATA ANALYSIS

The significance of the results was evaluated with the Student's one-sample *t* test (two-tailed). The differences were considered to be statistically significant when $p < .05$.

The average time-weighted oxygen consumption ($\dot{V}O_2$) and respiratory quotient (RQ) were calculated for each of the participants from the values recorded during the last 3–4 min of a particular activity. Each participant's metabolic rate for a particular activity was calculated using the average time-weighted values of $\dot{V}O_2$ and RQ. M_{Meas} for a particular activity was calculated as an average of each participant's values for that activity.

The mean heart rate for each activity was calculated from the heart rates recorded at 10 s intervals during the last 3–4 min of the activity performed by the participant. The index of cardiac strain: Net Cardiac Cost (NCC) = Work heart rate – Rest heart rate (Chamoux, Borel, & Catilina, 1985; Lablanche-Combier & Ley, 1984) was used for the evaluation of work strain. The interpretation of NCC can be found in the study by Chamoux et al. (1985).

4. RESULTS

Two of the participants had a slightly higher M_{Rest} (the average difference was 1 and 4 W/m^2 or 1.5 and 6.5% of M_{ISO} respectively) than M_{ISO} for resting (Table 2). The Edholm scale does not have a category for M_{Rest}, but for the category “Lying, sitting, break” the metabolic rate value is 55 W/m^2.

TABLE 2. Descriptive Statistics of M_{Meas} Versus M_{ISO} and M_{Edh} of Each Activity

Physiological Measure	Descriptive Statistics: Mean/ Median	*SD*	Minimum	Maximum	M_{Edh}	M_{ISO}
REST						65
M_{Meas}	58.1	6.4	46.0	69.0		
Heart rate (HR)	69.2	9.8	52	94		
TASK 1					65	69
M_{Meas}	64.5	8.0	50.4	80.8		
Heart rate (HR)	74.5	8.3	63	101		
Borg scale (RPE)	8		6	14		
TASK 2					130	119
M_{Meas}	79.6	10.0	60.0	98.3		
Heart rate (HR)	77.7	8.6	66	104		
Borg scale (RPE)	11		6	17		
TASK 3					130	139
M_{Meas}	86.2	13.5	61.9	110.1		
Heart rate (HR)	81.6	8.5	68	100		
Borg scale (RPE)	12		6	17		
TASK 4					130	84
M_{Meas}	65.3	8.7	50.7	89.1		
Heart rate (HR)	84.4	8.5	67	106		
Borg scale (RPE)	9		6	15		
TASK 5					130	104
M_{Meas}	84.1	11.8	65.1	113.6		
Heart rate (HR)	86.1	10.1	52	107		
Borg scale (RPE)	11		6	15		
TASK 6					220	154
M_{Meas}	120.7	19.9	82.7	175.5		
Heart rate (HR)	94.6	9.4	79	122		
Borg scale (RPE)	15		7	19		

Notes. M_{Meas}—measured metabolic rate (W/m^2), M_{Edh}—metabolic rate derived from the Edholm scale (W/m^2), M_{ISO}—metabolic rate derived from Standard No. ISO 8996 (ISO, 1990; W/m^2), M_{Rest}—morning resting metabolic rate (W/m^2), HR—heart rate (beats/min).

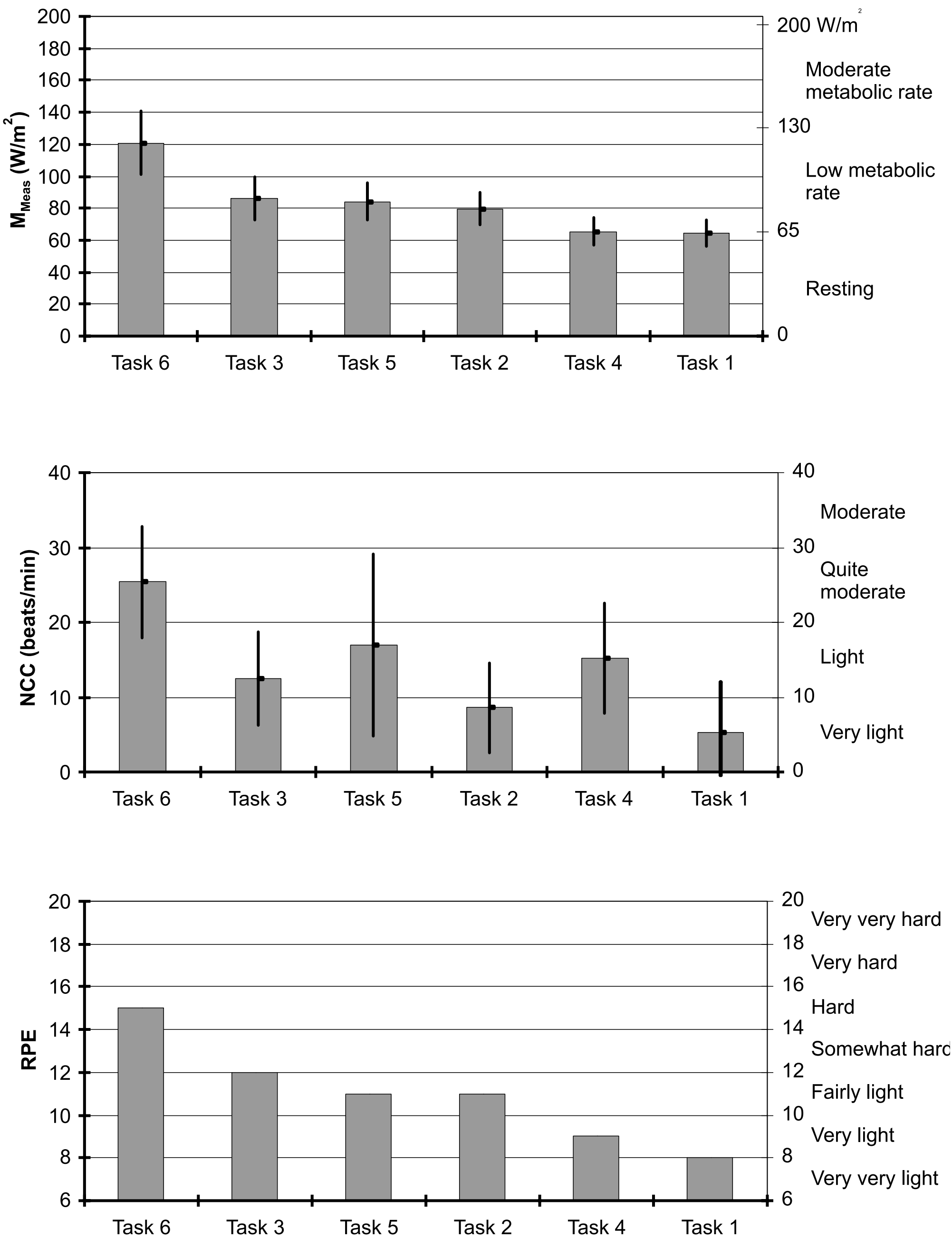

Figure 1. Evaluation of work strain according to M_{Meas} (W/m^2), NCC (beats/min), and the Borg scale (RPE). The average values of M_{Meas} and NCC, and the median of RPE are given in thick bars. Thin bars denote standard deviation. *Notes.* M_{Meas}—measured metabolic rate, NCC—Net Cardiac Cost, for description of tasks 1–6 see Table 1.

In the conducted study M_{ISO} overestimated M_{Meas} for all tasks by 7–38%. Similarly to the comparison with Standard No. ISO 8996 (ISO, 1990), the Edholm scale overestimated M_{Meas} for all tasks except task 1. M_{Edh} agreed with M_{Meas} solely for task 1 in this study, whereas M_{Meas} for the other five tasks were overestimated even more than by M_{ISO}, that is, by 34–50% of M_{Edh}.

Comparison of the M_{ISO} values with each participant's M_{Meas}, indicates both under- and overestimation. The M_{Meas} values from task 1 were lower than M_{ISO} for 11 participants (the range of difference was 4–19 W/m^2 or 6–27% of M_{ISO}), higher for 7 other participants (4–12 W/m^2 or 6–17% of M_{ISO}) and one value equalled M_{ISO}. The M_{Meas} values were considerably lower than M_{ISO} for all participants while performing task 2 (21–59 W/m^2 or 17–50% of M_{ISO}) and task 3 (29–77 W/m^2 or 21–55% of M_{ISO}). Tasks 4, 5, and 6 were performed at lower M_{Meas} than M_{ISO} by 18 participants. The differences between M_{ISO} and M_{Meas} were 11–30 W/m^2 or 13–37%, 2–39 W/m^2 or 2–37%, and 10–67 W/m^2 or 7–44% for the respective tasks. M_{Meas} was higher than M_{ISO} for only 1 participant for task 4 (10 W/m^2 or 9% of M_{ISO}) and for another participant for task 5 (10 W/m^2 or 9% of M_{ISO}). Both of these participants had higher M_{Meas} than other participants had on average for the tasks performed. M_{Meas} equalled M_{ISO} for one participant under task 6.

The evaluation of work strain according to M_{Meas} (W/m^2), NCC (beats/min), and the Borg scale (RPE) is given in Figure 1. All of the results from M_{Meas}, NCC, and the Borg scale gave similar indications in the evaluation of strain of the participants. In fact, with reference to both M_{Meas} and NCC, the values obtained indicated that the work load was moderate-light for task 6, whereas the other activities were indicated as light. The subjective evaluation of perceived exertion gave the same results: task 6 was rated as hard, whereas other tasks were indicated as fairly light to very light.

No differences in the work manner adopted by participants were observed in tasks 1, 3, 4, and 5. Differences were observed in the work posture (task 6) and the work technique (tasks 2 and 6) adopted by participants while performing the tasks.

5. DISCUSSION

The ISO standardisation helps to avoid similar scales with similar wording in the tabulated values corresponding to different values of metabolic rate, which usually causes problems in practical field work.

Attempts have been made to modify the Edholm scale. Long and Louhevaara (1992) proposed a modified Edholm scale for manual handling jobs, based on the results of several studies on manual handling of postal parcels (Long & Louhevaara, 1992; Louhevaara, Hakola, & Ollila; 1990; Louhevaara, Teräslinna, Piirilä, Salmio, & Ilmarinen, 1988).

The results of the present study are consistent with those reported by Ilmarinen et al. (1979) and Kähkönen et al. (1992). The study by Ilmarinen et al. (1979) showed that occupational activities in industries with no heavy physical work had been overestimated by the Edholm scale in the categories "Sitting or standing with very light movements or activities" and "Activities with low intensity," therefore they should be placed one category lower. The study of Kähkönen et al. (1992) reported that the metabolic rate derived from the Edholm scale was higher than that from the Standard No. ISO 7243 (ISO, 1989) tables.

The ISO standard sets an acceptability limit of 15% for relative errors calculated for the different indirect methods and ±5% for measurements and time studies. Thus, if these acceptability limits are considered, only M_{ISO} for tasks 1 and 5 is the same as M_{Meas}. However, even after considering the error limits M_{Edh} does not become equal to M_{Meas}.

In addition, Standard No. ISO 8996 (ISO, 1990) states that the metabolic rate can vary from person to person by about ±5% for the same work and under the same working conditions. According to the standard, metabolic rate values vary within certain limits because of the influence of work technique, work speed, and differences between work equipment. Those participating in the present study used different techniques in tasks 2 and 6, whereas in the other tasks no differences were observed. As these inter-individual differences were observed even in very stereotyped tasks under laboratory conditions, it is concluded that the habits and the work procedures adopted by the participants are very important in determining energy expenditure under field conditions. All the participants used the same equipment during the entire experiment, thus the variation of M_{Meas} from participant to participant did not result from the use of different equipment. However, three of the tasks were not paced by the experimenter and this might have been a source of the differences in M_{Meas} values.

The energy cost of singular tasks in the Standard No. ISO 8996 (ISO, 1990) tables or the Edholm scale are given for a standard male person (1.7 m height, 70 kg weight, and a body surface of 1.8 m^2), which can explain errors for participants differing from the standard. The anthropometric characteristics of the average person calculated for the participants of the present study are close to those indicated in the standard, although the range of values was rather wide: height 1.55–1.92 m, weight 56–110 kg, and body surface 1.59–2.26 m^2. Additionally, the average participant in this study was younger (range of 21–38 years) than the reference person (35 years old) in Standard No. ISO 8996 (ISO, 1990). However, if the participants had been older an even a greater overestimation of M_{Meas} could be expected as the loss of fat-free mass (FFM) and reduction in basal metabolic rate (BMR) are believed to occur with ageing (Forbes, 1976; Tzankoff & Norris, 1977).

Some of those participating in this study were engaged in sports like aerobics, running, or jogging on a daily basis, whereas others were practising some kind of sport occasionally. The authors did not ask the participants for details of their training program, so the effect of the training is not clear. However, studies conducted (Alméras, Mimeault, Serresse, Boulay, & Tremblay, 1991; Meijer et al., 1991) suggested that the energy costs of daily physical activities were not different between trained and untrained participants. Furthermore, their experimental data also indicated that exercise training had a significant enhancing effect on resting metabolic rate.

The participants of the study represented three ethnic groups: Asians (4), Europeans (13), and Africans (2). There is some evidence suggesting that there are ethnic differences in the energy cost of standard activities. Energy expenditure for lying, sitting, and standing was reported to be lower in Africans and Asians living in Great Britain compared with Europeans, in participants matched by body dimensions (Geissler & Aldouri, 1985). However, there were no significant differences in BMR, or in the energy cost of lying, sitting, and standing between Gurkha soldiers stationed in Great Britain and British controls matched by body weight and occupational background (Strickland & Ulijaszek, 1990). Thus, it is left unknown if the fact that the participants were of three different races somehow influenced the results of the study.

The subjective evaluation of perceived exertion was more correlated to M_{Meas} than to NCC, which is in contrast to the consistency with the Borg scale. The same observation of HR inconsistency with the Borg scale was reported by Costa, Berti, and Betta (1989). It is plausible that the subjective evaluation of work strain does not refer only to the overall sensation of]fatigue, but also to local strains, in particular on the musculoskeletal system due to bad postures or repetitive movements. For the same level of energy expenditure, it is known that HR is influenced by the mass of active muscles, the type of muscular contraction (dynamic or static), the thermal environment, and the physiological and psychological state of the participant (Horwat et al., 1988). HR may vary at each level of oxygen consumption, depending on which muscle groups are active (Åstrand & Rodahl, 1977). It is well known that for a given $\dot{V}O_2$, heart rate is higher for static work than for dynamic work (Kilbom, 1976) and higher for work with small muscle groups than for work with large muscle mass (Stenberg, Åstrand, Ekblom, Royce, & Saltin, 1967).

The Edholm scale expresses the metabolic cost of physical activity as a multiple of BMR. It is based on two assumptions: first, that the inter-individual variability in total energy expenditure for any group of participants is reflected in their BMR (Shetty & Soares, 1988), and secondly, that BMR can, for reasons of simplicity, be predicted from body weight using linear equations specific for age and sex. The part of the Edholm scale dealing with BMR was not examined in this study. Thus for the full validation of the Edholm scale, studies correlating actual measured metabolic rates with those estimated as multiples of BMR should be conducted on different levels of work load.

6. CONCLUSIONS

M_{Edh} overestimated the energy costs of five activities, and only the M_{Edh} value of task 1 was the same (at significance level $\alpha = .05$) as M_{Meas}. Even after considering the acceptability limit of 15% for the relative errors calculated for the different indirect methods, and ±5% in measurements and time studies, the M_{Edh} values were still higher than M_{Meas}. M_{ISO} overestimated all of the activities, but if the accepted error limits are considered, the M_{ISO} values for tasks 1 and 5 were equal to those of M_{Meas}.

As the overestimation of the metabolic rate for the particular activities was sometimes up to 50% of M_{ISO}, it is recommended that the values of metabolic rate given in Standard No. ISO 8996 (ISO, 1990) for moderate and especially light activities should be reviewed. The same recommendation applies to the Edholm scale.

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