



COMPARISON OF ACCURACY OF VARIOUS NON-CALORIMETRIC METHODS MEASURING ENERGY EXPENDITURE AT DIFFERENT INTENSITIES

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ABSTRACT

Purpose. The purpose of the study was to evaluate the accuracy of three non-calorimetric methods' measurements of energy expenditure (EE) in laboratory conditions and to compare the results obtained by each method in free-living condition in a group of adult subjects. **Methods.** Measurement was performed on 20 individuals aged 19–39 years. An assessment of EE at different intensities of physical activity was conducted by: monitoring heart rate with a S-610 Polar Sport Tester (HRM), measuring body movement by an ActiGraph GT1M accelerometer (AM), and recording METs (MR) by a physical activity questionnaire, for different activities (leisure and exercise) at various intensities in laboratory and free-living conditions. Indirect calorimetry (Cosmed K4b2 respirometer) was used as a reference standard. **Results.** The most reliable tool for EE assessment was HRM (100% accurate). AM overestimated EE (about 60%) for activity at moderate-intensity and underestimated EE (about 40%) at vigorous-intensity. MR overestimated the results, with measurement errors increasing with an increase in physical activity intensity (about 40–120%). **Conclusions.** Although AM and MR provided less accurate results than HRM in laboratory conditions, there were no significant differences between the three methods (HRM, AM and MR) when total daily energy expenditure was calculated for the participants in free-living condition.

Key words: energy expenditure, method accuracy, exercise, energy metabolism/physiology

Introduction

Research indicates that 50% of health is determined by lifestyle, including making healthy diet choices and performing enough physical exercise [1, 2]. Unfortunately, irregular lifestyles, low physical activity levels, and poor nutrition are observed ever more frequently among today's youth, placing this generation at a greater risk for developing adverse health effects in the future [3–5].

In order to better screen and identify at-risk individuals, some preventive medicine strategies include measuring daily energy expenditure (EE) and physical activity levels (PAL) [6, 7]. Such methods can quickly assess whether one's energy supply is properly balanced, preventing excess weight gain and obesity as well as other lifestyle diseases [8]. However, an accurate assessment of energy expenditure and physical activity level requires the use of measurement tools that need to take into account a wide variety of human activities, functions, and lifestyles. Furthermore, the various methods available for calculating daily energy expenditure possess a number of limitations. Although direct calorimetry is considered to be the gold standard in EE measurement, it is a costly technique and requires the use of special calorimetry chambers that prevent analysis in natural conditions, such as during normal activities of daily living [9, 10].

Similarly, methods using doubly labeled water are also quite expensive, and these techniques are also unable to determine energy expenditure during various life activities and forms of physical activity [9, 11]. Advances in technology have made it possible to construct portable respirometers that continuously measure oxygen consumption and exhaled carbon dioxide (a form of indirect calorimetry), allowing energy expenditure to be precisely determined in a wider range of daily activities [9, 10, 12, 13].

However, this method also features a number of drawbacks, such as the high cost of the measuring apparatus and the need to always breathe through a special mask or mouthpiece, making it difficult to conduct research over longer periods of time. Nonetheless, the high accuracy coupled with the relatively low cost of indirect calorimetry has allowed it to be used as a new reference standard in evaluating simpler, non-calorimetric methods that can measure energy expenditure and physical activity.

Some of the most commonly used non-calorimetric methods include monitoring heart rate and body movement (heart rate monitors and accelerometers). Questionnaires and physical activity logs are also used, paired with tables that can estimate the energy cost of various activities. The greatest advantage of the above methods is their low cost and noninvasiveness. In addition, these measurement tools are designed to be easy to use and allow participants to go about their natural lives with no restrictions on the type of activity, its duration or inten-

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sity [12, 14]. However, the accuracy of such instruments is of critical importance, as they may provide incorrect results or be unsuitable for various research purposes. In addition, the various non-calorimetric methods available for estimating energy expenditure have been frequently evaluated only by comparing one of them against a reference method [13, 15, 16], with few studies having conducted a simultaneous assessment of several measurement methods at the same time. This is unfortunate, as analysis performed under similar research conditions could help eliminate factors that may distort the results, especially when comparing similar measurements. Moreover, in order to obtain results of a practical nature it is important to validate measurements performed both in laboratory and “free-living” conditions. Assah et al. [17] believe that the measuring procedures used in laboratory testing do not fully reflect the physical activity patterns observed in uncontrolled, natural conditions. The authors also added that testing performed in “free-living” conditions allows for observation of a wider range of differentiated forms of physical activity.

With the above in mind, the purpose of this study was to assess and compare the energy expenditure values measured by various non-calorimetric methods with those attained by indirect calorimetry when performing different forms of physical activity in laboratory conditions, and to also compare the results of the non-calorimetric methods in more natural, “free-living” conditions.

Material and methods

Twenty individuals participated in the study, 11 women, aged 26.0 ± 4.5 years, and 9 men, aged 26.5 ± 5.0 years, all of whom led normal life activities. Before the start of the study, the participants' body mass and height were measured to calculate their body mass index (BMI) and metabolic body weight (body mass raised to the power of 0.73). Basal metabolic rate (BMR) was calculated after fasting and in stress-free conditions by indirect calorimetry using the K4b² portable gas respirometer (Cosmed, Italy). The participants were found to be in good health with none showing signs of obesity ($\text{BMI} \geq 30 \text{ kg/m}^2$).

Three non-calorimetric methods used to measure energy expenditure were assessed in laboratory conditions: by monitoring heart rate (HR) with a S-610 Polar Sport Tester heart rate monitor (Polar Electro Oy, Finland), by measuring body movement with a GT1M tri-axial accelerometer (ActiGraph, USA), and by recording physical activity in the form of questionnaire used to calculate the metabolic cost (MET, Metabolic Equivalent of Task) of the performed activities. Indirect calorimetry was assessed with the previously-mentioned K4b², continuously analyzing (breath-by-breath) the volume of inhaled and exhaled air as well as changes in gas concentration between oxygen uptake and expiration. The port-

able gas analyzer was calibrated each time before use with a reference gas mixture of: CO_2 – 5%, O_2 – 16%.

The taking of measurements by the three non-calorimetric methods and indirect calorimetry as a reference were performed in laboratory conditions, beginning each time in the morning after the participants had consumed an easy to digest breakfast (average energy value of 600 kcal, composed of 13% protein, 57% carbohydrates, and 30% fat) and continued for five hours in successive stages reflecting an average breakdown of the participants' normal daily routine, which had been previously recorded during a pilot study. The breakdown came to: sleep, lasting 94 min and 30 s, which accounted for 31.5% of the day; light-intensity activity (i.e. reading, writing, working at a computer, or watching TV) performed in a seated position, lasting 133 min and 30 s, which accounted for 44.5% of the day; moderate-intensity activity (simulated by walking, various laboratory exercises, preparing meals, or washing dishes), lasting 69 min, accounting for 23.0% of the day; and vigorous-intensity activity (performed on a CX1 cycle ergometer [Kettler, Germany] at an intensity of 70% $\text{VO}_{2\text{max}}$ at 150 W so as to reach heart rate values of 170–180 bpm), lasting 3 min, which accounted for 1.0% of the day.

The first 15 min of the test were treated as an adaptation period and were omitted from the final results. In addition, 10-min pauses were introduced between each activity phase and also not recorded. The calibration techniques recommended by Livingstone et al. were adhered to during measurement taking [18]. The obtained data were then proportionally calculated and presented as total daily energy expenditure.

Energy expenditure measured with monitoring heart rate is based on the physiological relationship between heart rate and metabolic rate, which is a result of the body's need to deliver sufficient levels of oxygen and energy substrates. The heart rate monitor (S-610 Polar Sport Tester) used in this method consisted of a cardiac pulse transmitter placed on the chest around the area of the heart by a rubber strap and a wrist monitor that recorded the amount of beats per minute. A correct estimate of EE was preceded by first performing regression analysis between oxygen uptake (VO_2) and heart rate (HR) – VO_2/HR – for each individual. This assessment was aided by the values recorded during indirect calorimetry at various intensity levels (lying, sitting, standing, walking, and riding the ergometer). In accordance with the procedure recommended by Bradfield et al. [19] and Livingstone et al. [18], the HR values obtained from earlier VO_2/HR calculations were used to delineate threshold heart rate, or HR-FLEX (as the average between the highest heart rate at rest and the lowest exercising heart rate), creating a individually established threshold between activities performed at light intensity and those of at least moderate physical activity. After HR-FLEX was calculated for each participant, the heart rate recorded throughout the measurement period was cate-

Table 1. Estimating individual total daily energy expenditure based on heart rate measurement

Type of activity	Equation	Legend
EE during sleep	$EE = ST/1400 \times BMR$	ST – Sleep time BMR – Basal metabolic rate
EE at light-intensity activity (HR < HR-FLEX)	$EE = BMR/1440 \times DE_p \times 1.4$	DE _p – duration of effort at light intensity (min)
EE at moderate- and vigorous-intensity activity (HR ≥ HR-FLEX)	$EE_{min} = (ax + b) \times 4.9$	EE _{min} – energy expenditure (kcal/min) a – linear regression slope coefficient (VO ₂ /HR) x – HR (bpm) b – linear regression intercept coefficient (VO ₂ /HR) 4.9 – energy equivalent for oxygen (kcal/dm ³)

BMR calculated by indirect calorimetry using the K4b² respirometer.

ogized into four types of activity depending on their intensity [18], with energy expenditure calculated using the procedure described in Table 1.

The second non-calometric method for measuring energy expenditure (EE) was performed with an accelerometer, which provides an objective assessment of all physical activity performed over a period of time as well as its duration and intensity [20]. The accelerometer is a lightweight, waterproof, and noninvasive tool, and it can record body movement in the vertical, lateral, and longitudinal directions. With this method, energy expenditure (EE) associated with physical activity is calculated by the use of an intrasystemic algorithm, composed of two equations [21]. For light-intensity activity (counts < 1952, i.e., < 3.0 METs; with 1 count equal to 16.6 mg/s at 0.75 Hz), the Work-Energy Theorem is used: $EE \text{ (kcal/min)} = \text{counts/min} \times 0.0000191 \times \text{body mass (kg)}$. For moderate- and vigorous-intensity activity (counts ≥ 1952, i.e. ≥ 3.0 METs), Freedson's equation is used: $EE \text{ (kcal/min)} = 0.00094 \times \text{counts/min} + 0.1346 \times \text{body mass (kg)} - 7.37418$. Total daily energy expenditure (kcal) at different intensities of physical activity is then calculated by:

$$EE = EE_{pa} + BMR \times D_{pa},$$

where

EE_{pa} – energy expenditure associated with physical activity,

D_{pa} – duration of physical activity at a given intensity.

Energy expenditure during sleep was calculated the same way as in the method monitoring heart rate (Tab. 1).

The third non-calometric method used for measuring energy expenditure involved a physical activity questionnaire used to register the type and duration of all activity the participants performed. The activities were cross-indexed to compute their MET values (kcal/h/kg BM), where one MET represents 1 kcal burned per 1 kg of body mass (BM) in 1 h at complete rest, and it is equivalent to oxygen uptake of about 3.5 ml/kg of body mass.

The three non-calometric methods were also assessed in “free-living” conditions, with the participants leading their normal life activities over two 24-h periods

over three days (two weekdays and one day off from work), excluding the time spent sleeping. All three methods were used at the same time, meaning the participants wore the Polar Sport Tester heart rate monitor and the ActiGraph accelerometer and logged their physical activity by use of the questionnaire. The data collected were used to calculate total daily energy expenditure

Statistical analysis of the collected data was performed using Statistica v. 7.1 (Statsoft, USA), which included checking for straight-line correlations, one-way analysis of variance (ANOVA) post hoc Tukey's test if the results were statistically different; the level of significant was set at $\alpha = 0.05$.

Results

The anthropometric characteristics of the group are presented in Table 2. An assessment of the participants' nutritional status with BMI index found that both the males and females generally featured adequate BMI levels ($24.4 \pm 3.7 \text{ kg/m}^2$ and $21.9 \pm 3.4 \text{ kg/m}^2$, respectively), although the results were largely dispersed with a number of individuals who were underweight (BMI < 18.4 kg/m^2) or overweight (BMI > 25 kg/m^2). Large differences among the group were also found after calculating the physical activity level (PAL) for each participant, based on the ratio of total metabolic rate to basal metabolic rate, and ranged from 1.02 to 2.42.

Table 3 contains the energy expenditure values of physical activity performed at different intensities from using the three non-calorimetric methods and indirect calorimetry. Significant differences ($p < 0.05$) in measured energy expenditure were found between the physical activity questionnaire (measuring METs) and the accelerometer (ActiGraph GT1M) at rest; between indirect calorimetry (K4b² gas analyzer) or heart rate (S-610 Polar Sport Tester) and the accelerometer at moderate-intensity activity; between indirect calorimetry or heart rate measurement or the physical activity questionnaire and the accelerometer at vigorous-intensity activity. Although the total daily energy expenditure (TDEE) values measured by the various methods in laboratory conditions did not significantly differ, the discrepancy in TDEE

Table 2. Anthropometric characteristics and basal metabolic rate (BMR) of the participants

Parameter	Women <i>n</i> = 11		Men <i>n</i> = 9	
	$\bar{x} \pm SD$	Min – max	$\bar{x} \pm SD$	Min – max
Age [years]	26.0 \pm 4.5	19.0 – 36.0	26.5 \pm 5.0	23.0 – 39.0
Basal metabolic rate (BMR) ¹ [kcal/day]	1135.2 \pm 192.6	960.2 – 1441.5	1240.1 \pm 87.1	1114.4 – 1458.6
Body mass [kg]	60.1 \pm 9.1	65.0 – 100.0	77.7 \pm 14.0	47.0 – 83.0
Body height [cm]	165.9 \pm 5.4	166.0 – 191.0	178.0 \pm 8.4	152.0 – 173.0
BMI [kg/m ²]	21.9 \pm 3.4	18.2 – 29.9	24.4 \pm 3.7	17.7 – 29.4
Metabolic body weight [kg ^{0.73}]	19.9 \pm 2.2	21.1 – 28.8	23.9 \pm 3.1	16.6 – 25.2
Physical activity level (PAL) ²	1.61 \pm 0.42	1.07 – 2.42	1.52 \pm 0.39	1.02 – 2.07

¹ BMR calculated by indirect calorimetry, ² PAL during “free-living” conditions: ≤ 1.4 – sedentary lifestyle; 1.55–1.6 – moderately active lifestyle; ≥ 1.75 – vigorously active lifestyle [22]

Table 3. Assessment of energy expenditure measured by the three non-calorimetric methods versus indirect calorimetry at different physical activity levels

Method	Activity intensity level				
	Sleep [kcal/kg BM/ duration]*	Light intensity [kcal/kg BM/ duration]	Moderate intensity [kcal/kg BM/ duration]	Vigorous intensity [kcal/kg BM/ duration]	Total daily energy expenditure [kcal/kg BM/day]
Indirect calorimetry (K4b ²)	7.7 \pm 1.7 ^a	14.6 \pm 3.5 ^a	14.0 \pm 4.3 ^a	1.0 \pm 0.3 ^a	37.3 \pm 8.3 ^a
Questionnaire (METs)	6.8 \pm 0.5 ^a	17.9 \pm 7.5 ^b	18.3 \pm 5.2 ^{ab}	2.2 \pm 0.8 ^b	45.2 \pm 10.9 ^a
Accelerometer (ActiGraph)	7.5 \pm 0.6 ^a	12.5 \pm 2.8 ^c	22.5 \pm 14.6 ^b	0.6 \pm 0.3 ^c	43.1 \pm 17.4 ^a
Heart rate (Polar Sport Tester)	7.5 \pm 0.6 ^a	14.1 \pm 3.6 ^a	13.3 \pm 4.0 ^a	1.0 \pm 0.3 ^a	36.0 \pm 6.7 ^a

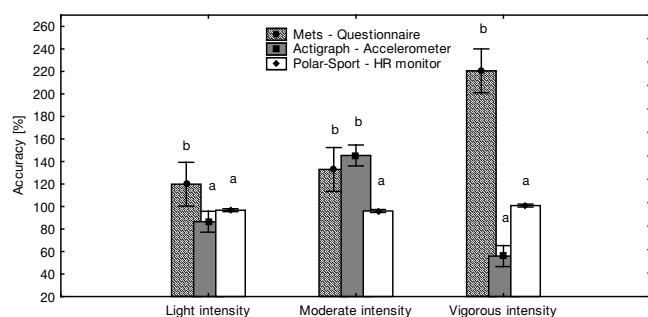
^{a, b, c} – inscriptions denote statistically significant differences ($\alpha = 0.05$) of the values in the columns

* time spent at each physical activity level, including: sleep – 454 min (7.6 h) = 31.5% of the day (the resting metabolic rate was adopted as the energy expenditure of sleep for the accelerometer and heart rate methods)

light-intensity activity: 641 min (10.68 h) = 44.5% of the day; moderate-intensity activity: 329 min (5.48 h) = 23.0% of the day
vigorous-intensity activity: 16 min (0.27 h) = 1.0% of the day

values assessed by the K4b² portable gas analyzer or by monitoring heart rate, and the physical activity questionnaire or the accelerometer, was between 15–20%.

An assessment of EE measurement accuracy by the three non-calorimetric methods and compared against those recorded by indirect calorimetry are presented in Figure 1. On the basis of the results, it was found that monitoring heart rate with the Polar Sport Tester was



^{a, b} – inscriptions denote statistically significant differences ($\alpha = 0.05$) of the values

Figure 1. Accuracy of energy expenditure measurements by three different non-calorimetric methods

the most reliable tool in measuring EE at rest as well as at moderate and vigorous physical activity (accuracy of 95%–100%). The method using the accelerometer (ActiGraph) overestimated EE at moderate intensity by 60% and underestimated EE by 40% at vigorous intensity (the exercise test on the cycle ergometer). However, the accelerometer was 86% accurate in measuring EE at light intensity in relation to the values measured by indirect calorimetry. Out of all the methods used to measure energy expenditure, the least accurate was that using the physical activity questionnaire and correlating the answers with MET values. This method overestimated energy expenditure with ever larger measurement errors as the physical activity intensity increased: being 20%–30% off for activity at light intensity to 120% off for vigorous intensity.

Statistical analysis of the results confirmed that the physical activity questionnaire (calculating METs) was significantly less accurate ($p < 0.05$) than the other measurement methods by overestimating energy expenditure at light and vigorous intensity levels. Furthermore, energy expenditure assessed by the accelerometer (ActiGraph)

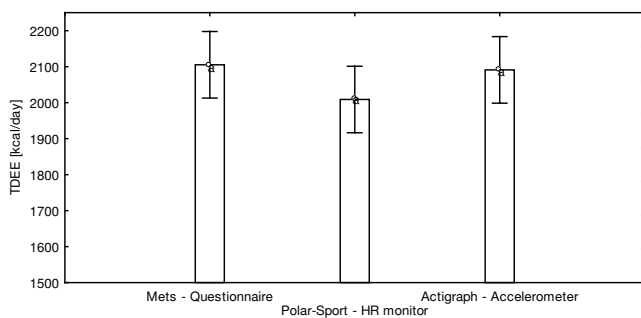


Figure 2. Comparison of total daily energy expenditure values recorded in “free-living” conditions by the three different non-calorimetric methods

and physical activity questionnaire (METs) at moderate intensity were significantly less accurate ($p < 0.05$) than by monitoring heart rate.

Figure 2 provides a comparison of total daily energy expenditure by the three non-calorimetric methods in “free-living” conditions. In comparison with EE based on monitoring heart rate (Polar Sport Tester), whose measurement accuracy in laboratory conditions was confirmed by indirect calorimetry, both the accelerometer and questionnaire methods overestimated total daily energy expenditure by 5%. However, no statistically significant differences in total daily energy expenditure were found among the three non-calorimetric methods.

Discussion

The present study estimated energy expenditure by monitoring heart rate, using an accelerometer, and recording physical activity on questionnaire to calculate METs, and compared the results with those attained by indirect calorimetry using a K4b² respirometer. The most accurate of the non-calorimetric methods was monitoring heart rate using the S-610 Polar Sport Tester heart rate monitor, with an accuracy close to 100%. These results are in line with previous observations on the reliability of this method by other researchers. Goodie et al. [23] found a high correlation ($r = 0.98$, $p < 0.001$) between heart rate measurements using a Polar Vantage XL heart rate monitor and those obtained using electrocardiography (ECG). In turn, Maffei et al. [16] validated this measurement technique and its accuracy in non-obese children by comparing it with energy expenditure measured using doubly labeled water. Garet et al. [24] conducted a study on verifying measurement of energy expenditure by heart rate with the gold standard of EE assessment, direct calorimetry. They found that measurement of physical activity levels and energy expenditure by heart rate was quite accurate and did not differ with respect to the data obtained using the reference method.

An assessment of the accuracy of the ActiGraph accelerometer found it overestimated energy expenditure up to 60% during moderate-intensity effort when com-

pared to the reference values from indirect calorimetry, and that the obtained results showed the highest intra-group variability. This may be explained by the findings of Hustvedt et al. [25], who claimed that some accelerometers can wrongly interpret even small variations in walking gait (from 2 to 3 km/h), classifying it as moderate-vigorous instead of light intensity. Furthermore, Le Masurier et al. [26] noted that accelerometers may incorrectly record non-walking movement as walking, overestimating energy expenditure especially among individuals who often travel by car.

What was also of interest was that the accelerometer used in this study underestimated energy expenditure during vigorous-intensity activity by 40% in comparison with EE obtained by indirect calorimetry. This could be linked to this study’s use of the cycle ergometer to simulate vigorous exercise, as an accelerometer works primarily by measuring torso movement, and its placement on the waist may have only recorded movement made by the upper body and not the cyclical work performed by the lower limbs. A more correct measure of this type of effort may require the use of additional sensors in accelerometers, or the development of even more accurate intra-systemic algorithms in order to correctly estimate energy expenditure during cycling. Therefore, the conclusions set forth by Trost et al. [27] seem to be corroborated, they stated that the algorithms used in accelerometers to assess energy expenditure do not take into account all the various types of physical activity humans perform. However, it is worth mentioning that the predictive accuracy of the most commonly used methods to calculate energy expenditure on the basis of various physiological parameters was highest by measurements taken by an ActiGraph accelerometer with Freedson’s equation (73% accurate) [28].

In the present study, the least accurate data on energy expenditure at different exercise intensities in laboratory conditions were collected by the use of the physical activity questionnaire that calculated METs. This may be due to the need, among other factors, of maintaining a very detailed log of the duration and type of physical activity performed as well as problems connected with properly classifying and interpreting their impact on energy expenditure. Sergi et al. [29], in a study on an elderly population, found that this method underestimated the values of activity performed at light- or moderate-intensity in comparison with the results attained by indirect calorimetry. It is believed that changes in body composition and the functioning of the cardiovascular system may explain for these differences. Seale et al. [30] found that the use of a physical activity questionnaire to calculate METs (4.60 MJ/d for men and 3.42 MJ/d for women) significantly overestimated total daily energy expenditure when compared with the doubly labeled water method. Similarly, Milani et al. [31] performed a study on patients after coronary events, finding that energy expenditure estimated by a questionnaire was

far less reliable than a reference method (indirect calorimetry). They found that this method overestimated the results of an exercise test both before and after a 12-week cardiac rehabilitation program. Similar measurement errors were found in the present study, and, more interestingly, the magnitude of error increased with higher exercise intensity, indicating this is a systemic error. Thus, due to their low accuracy, both the physical activity questionnaire calculating MET values as well as the accelerometer methods should be limited to general population studies attempting to obtain only indicative total daily energy expenditure and physical activity levels.

As was mentioned, the physical activity questionnaire and accelerometer methods overestimated total daily energy expenditure at different activity intensities by 15% and 20%, respectively, than those recorded using the reference method. Although these results were found to be statistically insignificant, the size of this error may have a number of physiological repercussions, as the use of these methods to assess total daily energy expenditure may lead to erroneous assumptions on individuals' daily energy requirements.

In light of the results attained in laboratory settings, the data obtained in "free-living" conditions showed a surprisingly high convergence among the non-calorimetric methods. As monitoring heart rate in laboratory conditions deviated to a considerably lesser extent from the indirect calorimetry method in comparison with the other methods, it was expected that a similar variation would have been observed in natural conditions. However, the differences between the mean values of the three non-calorimetric methods amounted to only 5%, which corresponds to a deviation of approximately 100 kcal/d (0.4 MJ/d) between the evaluated methods. This is likely to be attributable to the fact that there was a greater range of different forms of physical activity being performed and at more varied intensities, hence the measurement errors could have mutually compensated each other [17]. As a result, it can be assumed that in many cases the practical application of any of the three methods can provide relatively close assessment of total daily energy expenditure, although attention needs to be paid to the questionnaire and accelerometer methods from overestimating the results even in "free-living" conditions. However, the results of this study should be used with some caution in regard to the population being studied, where in this case it comprised of individuals who were sedentary or moderately physically active.

Conclusions

Monitoring heart rate is a reliable method for assessing energy expenditure at different intensity levels. Energy expenditure measurements based on an accelerometer and in particular with the use of a physical activity questionnaire calculating MET values are less accurate,

where the questionnaire method showing a tendency towards measurement overestimation, with error increasing with activity intensity. On the other hand, the accelerometer both overestimated or underestimated results depending on the intensity or type of physical effort being performed. Nonetheless, each of the evaluated non-calorimetric methods can be successfully used to meaningfully assess total daily energy expenditure in more natural, "free-living" conditions, especially in a young sample group with low to average physical activity levels.

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