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Research Progress on Measurements of Energy Expenditure in Physical Activity

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***Abstract*—Accurate measurement of physical activity-associated energy expenditure (PAEE) helps to quantify exercise intensity and volume, also guides people to exercise scientifically and reasonably. This paper reviews several methods commonly used in PAEE measurement: direct observation, questionnaire, heart rate monitoring, calorimetry, doubly labelled water, and methods using data obtained by motion sensor, such as stride frequency, acceleration and velocity, to estimate PAEE. The pros and cons of various measurement methods are analyzed. It is proposed that research trend should be comprehensively utilize a variety of methods to improve the accuracy of PAEE measurement, while using smart phones and wearables as portable measuring devices for easy application.**

Keywords—indirect calorimetry; accelerometer; energy expenditure; physical activity

I. INTRODUCTION

Physical activity-associated energy expenditure (PAEE) refers to any increase in energy expenditure (EE) based on resting energy expenditure (REE), caused by physical activity (PA) which result from skeletal muscle contraction [1].

Nowadays, with the convenience of traffic conditions and the increasing automation of living facilities, people's PA is becoming less and less. In 1953, Morris et al. [2] found that the incidence of coronary heart disease (CHD) in London double-decker bus drivers was three times that of ticket sellers, proposed the close relationship between PA level and health. Subsequent studies have found that physical inactivity brings serious harm. Gracia [3] suggested that poor diet and lack of PA will lead to a decline in autoimmunity and promote the development of inflammatory diseases.

The danger of physical inactivity is so great. Increased PA can improve human immunity and vitality to improve people's health; simultaneously, it can prevent and control the occurrence and development of several high-risk chronic diseases. However, exercise blindly often fails to yield the desired results and may even cause sports injuries. Goodman et al. [4] suggested that strenuous PA significantly increased the risk of fatal and non-fatal cardiovascular adverse events compared to resting state. Merghani et al. [5] proposed a U-shaped relationship between exercise and heart disease incidence, suggesting that moderate-intensity exercise was better than non-exercise, but strenuous exercise may be harmful. Therefore, accurately measuring PAEE can help quantify the intensity and volume of exercise, so as to scientifically and reasonably guide different groups of people to exercise.

II. COMMON MEASUREMENT METHODS OF PAEE

Objective, accurate and reproducible measurement methods of PAEE can reflect the EE levels of different types of PA. Based on this, it is possible to accurately distinguish exercise intensity in order to evaluate the effectiveness of exercise intervention, which is increasing the corresponding PA in different groups of people. At present, commonly used measurement methods of PAEE usually include direct observation, questionnaire, heart rate monitoring, calorimetry, doubly labeled water and methods that estimating PAEE by data which acquired by motion sensor, such as stride frequency, acceleration and velocity. The various methods are briefly described below.

A. Direct Observation

Direct observation (DO) needs observer to observe the PA of specific object over a period of time while recording activity's type, frequency, and duration. Observer then quantifies object's PAEE according to the EE corresponding to various activities, so as to evaluate the level of PA.

Sirard et al. [6] proposed that DO is an effective and reliable measurement method of PA and can provide information on PA types and background in preschool children.

During the observation period object's PA can be completely recorded with high reliability and validity. However, it requires lots of effort and time to train the observer, which cost is high; the object needs to be observed one by one, which is difficult to apply in large sample research. Therefore, it is generally only applied in short-term and small sample study.

B. Questionnaire

This is a subjective method that most commonly used in the evaluation of PA research. The international physical activity questionnaire (IPAQ) is currently used, including two versions: long and short volume.

Macfarlane et al. [7] verified the reliability and effectiveness of the IPAQ long volume in Hong Kong adults,

found that it can distinguish four types of PA better (P=0.019) than accelerometer.

This method is simple and easy to implement with low cost, which is suitable for large sample research. However, the shortcoming is that the survey results are subjectively influenced by recalls. In addition, the types of activities involved in the report often do not cover all kinds of PA, resulting that some PAs' strength can not be accurately distinguished. Therefore, the reliability and validity of the questionnaire need to be verified when applied.

C. Heart Rate Monitoring

This method uses the stress on the cardiovascular system during PA to reflect the EE of the body. According to the Fink principle [8], the oxygen consumption is equal to heart rate multiplied by stroke volume and arteriovenous oxygen difference. Freedson et al. [9] found a linear relationship between heart rate and oxygen consumption when the heart rate is between 110~150 bpm. There is a constant relationship between oxygen consumption and heat generation of the body. Therefore, the PAEE can be estimated by monitoring heart rate.

However, the measurement of heart rate is more susceptible to many factors, including emotional changes, environmental temperature and humidity, results in a complicated relationship between heart rate and oxygen consumption. Considering that the heart rate can reflect the PA intensity in real time, many scholars have made improvements. The curve heart rate method (Flex-HR) proposed by Spurr et al. [10] largely breaks through its limitations. Livingstone [11] proposed that Flex-HR could be used as a standard tool for measuring daily energy expenditure in a free-living population. In addition, there were heart rate + motion sensor technologies proposed by follow-up scholars, such as Silvia et al. [12] combine global positioning system (GPS) signals with heart rate and acceleration data to assess the PAEE levels of adult commuters.

D. Calorimetry

1) Direct calorimetry:

Direct calorimetry (DC) involves placing subject in the metabolic chamber, collecting total amount of heat that is diverged by radiation, conduction, convection, and evaporation over a certain period of time, then converting it into a metabolic amount per unit time, that is, energy metabolism rate.

Yan et al [13] proposed an EE measurement equation for the metabolic chamber under freelance condition, so that the 24-hour EE prediction accuracy can reach 96%.

The result of DC is accurate, while the device required is complicated and can only accommodate one subject at a time, as well as the high cost, which limits its application that it is only suitable for small sample study. In that case, it is generally only used in studies such as obesity and endocrine system disorders.

2) Indirect calorimetry:

Compared with DC, indirect calorimetry (IC) as the "gold standard" [14] is much easier to apply, including two types: circulatory and open type. The principle is based on the proportional relationship between oxygen consumed by three major nutrients (carbohydrates, lipids and proteins) at the time of production and the carbon dioxide (CO_2) produced. EE is calculated by formula according to these two quantities.

For circulatory type, subject is required to breathe using a fixed closed device, quantitatively supply oxygen and collect CO_2 production, finally calculating the EE. This method doesn't need gas analysis to obtain oxygen consumption, but the subject's free movement is limited. The open type allows subject to breathe air freely. Gas analysis is usually performed using "breath by breath", which greatly enriches the test sample and provides a large amount of detailed test information.

Traditional gas analysis equipment is large in size and requires strict experimental conditions. The portable gas analysis equipment that has emerged in recent years has been favored by many researchers because of its real-time, portability, accuracy and excellent features. Gilgen-Ammann et al. [15] found that respiratory variables and age can be used to accurately determine the daily TEE of healthy adults in different ages and body types who performing different types of aerobic activities. However, it still has a certain influence on PA when the device is worn, and can not work continuously for a long time.

E. Doubly Labelled Water

In 1982, Schoeller and Van Santen [16] firstly applied the doubly labelled water (DLW) to human EE research. The subject takes certain amount water labelled by situ heavy hydrogen (^2H) and heavy oxygen (^{18}O). After digestion and absorption, using isotope mass spectrometer to measure ^2H and ^{18}O in blood, saliva or urine, then calculating CO_2 emission rate. Finally, the average daily TEE is obtained by using the classical Weir formula [17].

Smith et al. [18] used DLW to evaluate EE during 14-day in-season period in rugby player and found that their TEE was high, making the existing EE prediction equation unsuitable.

The result of DLW has high precision and can be used as the "gold standard" [19] for measuring TEE for several days. It also has few impact on human body during testing. However, due to the high cost, it is only suitable for small sample study. In addition, the required test time is at least 3 days and can only reflect the TEE, which limits its application range. In that case, DLW generally used as a standard for evaluating other EE measurement methods.

F. Other Measurement Methods

Using data obtained by motion sensor, such as stride frequency, acceleration and velocity, to estimate PAEE is a commonly used method, which is widely used in the fields of biological rehabilitation medicine, sports training, daily activity monitoring and the like. Depending on the motion sensor used, it can be generally divided into the following two types.

1) Indirect EE estimation method based on stride frequency:

This method primarily uses pedometer to acquire data such as steps and stride frequency, with the characteristics of small size and cheap, but it can not provide detailed information such as activity intensity and movement mode. Moreover, it can not

induce PA without obvious body movement (such as cycling). In that case, it is only suitable for obese people to simply self-monitoring.

Trapp et al. [20] tested the accuracy of using pedometers to measure the number of steps on a treadmill at 42, 66, and 90 m/min in youth population, and found that the slower the pace and the lower the stride frequency, the worse the accuracy.

2) Acceleration-based indirect EE estimation method:

Accelerometer is a commonly used motion sensor, which includes three types: single-axis, dual-axis, and three-axis. It works by using sensors (such as piezoelectric, piezoresistive and capacitive) to obtain acceleration signals during body motion, after that data such as acceleration and velocity is obtained through data processing to estimate PAEE. It is easy to carry, works without damage to the body, and has minimum interferes with normal activity.

Cawthon et al. [21] used the multi-sensor SenseWear Pro armband to measure PA and PAEE in men with unrestrained osteoporotic fractures, and recommended that this population should reduce sedentary time and increase moderate-intensity exercise time.

Mandigout et al. [22] found that 14 commonly used wearable sensors underestimated PAEE in post-stroke patients, indicating that the built-in energy prediction equations were not suitable for these people.

Sushames et al. [23] compared the differences in steps counting by using Fitbit Flex, direct observation and Actigraph accelerometers in the adults, found that Fitbit Flex measurement underestimated the steps.

Parak et al. [24] used heart rate in combination with running velocity and physiological parameters to estimate EE during running, found that compared with results measured by respiratory gas analyzer, the EE was estimated to be more accurate when the heart rate exceeded aerobic threshold while accuracy was reduced at lower exercise intensity.

The accelerometer measurement result for scientific research is accurate, but the operation is complicated as well as high cost. Accelerometers built into smartphones and wearables are a simple alternative, at a lower cost and can be measured continuously. Guidoux et al. [25] proposed the $Pred^{EE}$ algorithm for measuring the energy expenditure of different types of activities under free-living condition, compared with Armband, the total EE measurement error is 5.7%. However, the accuracy of the measurements obtained with these devices still needs to be improved.

III. SUMMARY

Among various measurement methods for PAEE, the reliability and validity of the DO are high, while the labor and material resources are huge, and it is not suitable for large sample study. The questionnaire has low implementation cost and is suitable for large sample research. However, its research results are subject to a variety of subjective factors. Heart rate monitoring is more accurate in a range of exercise intensity, but individualized differences in heart rate can lead to inaccurate results. DC is a good choice considering the accuracy of the measurement results. However, the experimental device is complicated, costly, and not suitable for large sample study. As "gold standard", IC is simplified, but the required equipment is still complex and costly. The DLW measures accurately and has small interference, but it only reflects the TEE information, and costs high. Using data such as stride frequency, acceleration and velocity obtained by motion sensor to estimate PAEE only requires a small volume, light weight device, which has less interference during exercise. However, professional guidance and high cost limit the promotion and application in large-scale population. As a simplified alternative, smartphones and wearables can be widely used, but it is still needed to continuously improve the measurement accuracy.

IV. OUTLOOK

In summary, various PAEE measurement methods have their pros and cons, while there is not a method suit for all PAEE measurement. Therefore, when selecting a research method, it is necessary to comprehensively consider multiple factors such as the research purpose, the sample size and the research funding. It is found that comprehensive utilization of multiple EE measurement methods has become a research trend, such as combining heart rate, acceleration and GPS data to improve the accuracy of measurement results. At the same time, with people's constant attention to their health, the use of smart phones and various wearables as data sources for EE measurement is easier to promote.

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