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Physical Activity Monitors: Do More Sensors Mean Better Precision?

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Abstract

Physical activity is essential to health. Accelerometry-based activity monitors are widely used in clinical and epidemiological research settings; however, only measuring body movement may prohibit accurate prediction of energy expenditure. Recent technological advancements allow synchronous measurements of heart rate, body temperature, acceleration, and other physiological responses and record them in detail (every minute or finer precision). Current multisensor devices are small, wireless, and capable of continuously recording data over several days or weeks, making them readily applicable in the free-living environment. Future studies should focus on developing strategies to optimize sensor data for accurate and robust predictions of clinically pertinent outcome parameters, such as total daily energy expenditure and physical activity energy expenditure. There is also a need for calibration instruments to allow users to standardize devices in their own laboratory or clinic. We also call for more transparency in publishing sensor properties and modeling algorithms, rather than proprietary or "black-box" prediction approaches.

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Advances in electronics and communication technology have created a society where multifunctional devices are accepted as routine and even necessities—for instance, cell phones serve as cameras, personal digital assistants, music and video players, global positioning systems, game consoles, Web browsers, and much more. Medical technologies have also benefited from these innovations, for example, artificial pacemakers and insulin pumps. Technology development is also expanding its application to a broader population in order to gain further insight into personal health. The interest in monitoring individual physical activity levels is rising as benefits of physical activity are being increasingly emphasized. Researchers and some health-conscious consumers are looking for innovative measurement technologies (or gadgets) that are accurate, reliable, practical, and affordable. In this issue of *Journal of Diabetes Science and Technology*, Andre and Wolf summarized several market-available devices, spanning from pedometers to what we consider as gold-standard references—indirect calorimetry and doubly labeled water. As these authors pointed out, some objective measurement devices only contain single-axis piezoelectric sensors and essential electronics whose only function is to store and output time-integrated movement counts. Although there are inherent limitations, this technology is the backbone

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of many devices used in clinical and epidemiological research to date. To exchange working ideas and unify research practices, in December 2004, many users, manufacturers, and developers in the physical activity monitoring field attended a special conference entitled "Objective Monitoring of Physical Activity: Closing the Gaps in the Science of Accelerometry" in Chapel Hill, North Carolina. Nine comprehensive review papers were published in *Medicine and Science in Sports and Exercise* (2005, Vol. 37, No. 11 Suppl.), covering calibration, experimental design and implementation, sensor technology, and data analysis in accelerometers, as well as the utilities of other sensors (heart rate and global positioning system).

We recognize that these existing single-site, single-axis accelerometers tend to lack in precision for predicting energy expenditure. Likely contributors are (1) incomplete assessment of overall body movements during certain activity types, (2) insensitivity to low-intensity activities, which can be dominate in free-living sedentary individuals, (3) time-averaged "counts" may lose potentially useful information in signal patterns, and (4) oversimplified regression or cut-point approaches to model activity intensity. New activity monitors have started to implement strategies to address some of these limitations. For example, IDEEA (MiniSun LLC) has five tethered accelerometers positioned at different sites; Actigraph (Actigraph Inc.), perhaps the most commonly used accelerometer to date, has modes to allow raw data collections (1-second epoch, or even at 30 Hz); and Actiheart (Mini Mitter Respironics) combines heart rate and acceleration and implements a branched model for low- and high-intensity activity-associated energy expenditure prediction.

The innovation of integrating physiological measurements with accelerometry may enhance energy expenditure prediction, particularly in sedentary conditions, low-intensity activities, activities with limited body movements (e.g., resistance exercise), and even under variable environmental conditions (temperature changes). The physical assimilations of multisensor arrays into portable wireless systems are being achieved in devices such as the Actiheart and SenseWear (BodyMedia, the parent company of the authors). However, other than a few small studies done with specific activity types and selected populations (usually young and lean normals), we have not seen significant improvements over their predecessors—single accelerometers—to which we raise the rhetorical question: Do more sensors necessarily mean better precision?

While a multisensor system may measure motion from different body segments (in the case of IDEEA) or may provide additional biological response measures (Actiheart and SenseWear), it is also conceivable that a single failure of an individual sensor could render the failure of the "all-or-none" monitoring system. For example, if one of the five IDEEA sensors stops working, the entire system will not work properly. Actiheart will not predict energy expenditure during periods of invalid heart rate, despite the presence of acceleration measurements. Also, when the skin temperature is not sufficiently detected by the SenseWear, the device will not initialize or will stop recording during a test.

Although the integration of sensors represents an important step, the advancement of these activity monitors is not complete without the construction of robust and accurate models for predicting the intensity of physical activity. The process of modeling first requires careful considerations of these key factors: (1) *Accurate and dynamic physical activity intensity reference data*. Ideally, these data are collected using indirect calorimetry carts and whole-room respiratory chambers. (2) *Appropriate modeling framework*. Both the IDEEA and the SenseWear first classify the type of activities, based on both postural and dynamic information from the sensors. These classifications can then be used to "map" activity measures to energy expenditure values using reference values in one or more look-up tables.[1,2] Minor adjustments to these values may also be made by incorporating subjects' weight, height, age, sex, and fitness assessments. However, this approach puts high demands on the precision of classification algorithms. Moreover, the contributions from different measurements/sensor are unknown to the researchers, thus errors because of individual sensor drifts or artifacts are difficult to determine. (3) *Adequate discloser of model information*. Some manufacturers prefer the use of "black-box" or proprietary algorithms over transparent models appearing in publications. However, the latter allows researchers to develop or modify models to enhance the performance of these devices, especially for special populations such as the obese, children, elderly, and other patients with specific diseases of interest.

Regular calibration is typically required to achieve optimum performance in most devices used for scientific measurement. This ensures that measurements both within and between devices are consistent over the course of many experiments. While virtually all physical activity monitors claim to be "calibrated by the manufacturer prior to delivery," it is often hard to assess the device performance after wear and tear that occurs with regular use during scientific studies. To our knowledge, the MTI (the predecessor of Actigraph) was the only accelerometer to include a manufacturer-supplied calibrator. The calibration device used a standard set of motion frequencies to test the response range of the accelerometer and allowed user adjustment as needed. The MTI calibrator does not work with the current Actigraph sensors (GT1M). However, to the credit of the company, the GT1M self-calibrates regularly to compensate for any sensor drifts. There is an acute need for analogous calibrators for each sensor incorporated into multisensor devices, such as the SenseWear, if we hope to achieve the added precision in outcome variables that these measurements can potentially provide. Such calibrators should provide feedback to the user about the response time and sensitivity of each sensor in the device using physiologically relevant perturbations and would serve to both reduce measurement variability and alert users to defective sensors in a timely fashion.

As physical activity monitoring moves into the future, it is incumbent on researchers to be open to new technologies, such as multisensor arrays, as well as integrating familiar sensors into new devices. Several cell phone manufacturers are already building activity monitors (accelerometers, gyroscopes, etc.) into cell phones in Europe and Asia, with the cell phone service providing the data download. Similar efforts are also currently underway in the U.S. cell phone industry. We anticipate more modes of activity-sensing technology now and in the not too distant future. But for the researcher, the key question still remains: How do we make *more* equal *better*?

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