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BALANCE (Bioengineering Approaches for Lifestyle Activity and Nutrition Continuous Engagement): Developing New Technology for Monitoring Energy Balance in Real Time

Deonna C. Hughes, B.S.,[1] Adrienne Andrew, M.A.,[2] Tamara Denning, B.S.,[2] Philip Hurvitz, M.F.R.,[3] Jonathan Lester, M.S.,[4] Shirley Beresford, Ph.D.,[1] Gaetano Borriello, Ph.D.,[2] Barbara Bruemmer, Ph.D., R.D.,[1] Anne Vernez Moudon, Dr.Sc.,[3] and Glen E. Duncan, Ph.D., R.C.E.P.$_{SM}$[1]

Abstract

Methods that measure energy balance accurately in real time represent promising avenues to address the obesity epidemic. We developed an electronic food diary on a mobile phone that includes an energy balance visualization and computes and displays the difference between energy intake from food entries and energy expenditure from a multiple-sensor device that provides objective estimates of energy expenditure in real time. A geographic information system dataset containing locations associated with activity and eating episodes is integrated with an ArcPad mapping application on the phone to provide users with a visual display of food sources and locations associated with physical activity within their proximal environment. This innovative tool captures peoples' movement through space and time under free-living conditions and could potentially have many health-related applications in the future.

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Introduction

The United States faces an epidemic of overweight and obesity,[1,2] major health concerns because they increase the risk of developing multiple chronic diseases.[3–5] These energy imbalance disorders thus result in a large public health burden.

In June 2006, the National Institutes of Health and the National Science Foundation convened a workshop, titled "Engineering Approaches to Energy Balance and Obesity: Opportunities for Novel Collaborations and Research" to identify important and understudied research topics in energy balance that could be addressed through innovative engineering approaches.[6] Methods to easily and accurately measure energy intake, expenditure, and balance in "real time" was one such identified area. Furthermore, aspects of the "built environment" that might

Author Affiliations: [1]Nutritional Sciences Program, Department of Epidemiology, University of Washington, Seattle, Washington; [2]Department of Computer Science and Engineering, University of Washington, Seattle, Washington; [3]College of Built Environments, University of Washington, Seattle, Washington; and [4]Department of Electrical Engineering, University of Washington, Seattle, Washington

Abbreviations: (BALANCE) Bioengineering Approaches for Lifestyle Activity and Nutrition Continuous Engagement, (GIS) geographic information system, (GPS) global positioning system, (MSB) multisensor board, (USDA) United States Department of Agriculture

Keywords: activity, energy balance, food diary, real-time assessment, self-monitoring

Corresponding Author: Glen E. Duncan, Ph.D., R.C.E.P.$_{SM}$, Nutritional Sciences Program, Department of Epidemiology, University of Washington, 305 Raitt Hall, Box 353410, Seattle, WA 98195; email address duncag@u.washington.edu

encourage higher levels of physical activity and better nutrition was also suggested as another promising and important area of contribution. Our interdisciplinary team, with expertise in computer science and engineering, epidemiology, exercise physiology, nutrition, and urban planning, received a grant under a subsequent funding opportunity from this initiative.

We sought to create a practical software platform that provides users with a real-time visual display of energy balance and locations of food sources and physical activity facilities within their proximal environment. By providing behavioral and environmental information simultaneously, this tool could help facilitate behavior changes associated with weight loss and maintenance goals and have numerous health-related applications for practitioners, researchers, and consumers alike. This article provides a brief overview of the development of the Bioengineering Approaches for Lifestyle Activity and Nutrition Continuous Engagement (BALANCE) tool and our ongoing and future work.

Rationale

Early studies demonstrated that self-monitoring of lifestyle behaviors such as food intake enhanced weight control programs.[7,8] However, keeping accurate food and activity records over an extended time is difficult, and measurement errors introduced by self-report methods are well established. For example, people tend to systematically underestimate food intake[9] and overestimate activity level.[10] From a methodological standpoint, these retrospective questionnaires are problematic because they are subject to recall bias and memory limitations, among other issues of concern. Alternatively, real-time data-capture methods hold promise because they attenuate some of these issues by inquiring about current conditions.[11]

More and more, investigators have begun to examine the potential use of technology as a tool to facilitate behavior change. For example, studies have successfully used an electronic food diary on a personal digital assistant to track dietary behaviors[12–15] and a combination of body-worn sensors and Internet/mobile phone technology to objectively monitor physical activity levels.[16,17]

Using a mobile phone application, Tsai and colleagues[18] describe a method whereby users enter food intake and physical activity to get information on energy balance in near real time. The mobile phone platform connects to a server over the Internet so users can see their recorded data in greater detail. The server also stores the food and activity data and sends reminder messages to the user to update their information. Similarly, the GoWear fit device by BodyMedia tracks energy expenditure by measuring physical activity objectively via an armband sensor that measures motion, heat flux, and skin temperature. The sensor is connected to a computer so the user can download the data, while a Web-based food diary is used to enter foods eaten to track energy intake and ultimately energy balance.

Our BALANCE mobile phone application is an extension of existing technologies, with several important improvements. First, our tool features the multisensor board (MSB), described in more detail in the next section. This small, wearable device provides objective information on physical activity type and amount in both time and space. Second, our current work focuses on optimizing the BALANCE food intake program so that it is easier to use than other commercially available programs and is accessible directly on the mobile phone instead of relying on a remote connection to a server. Finally, we provide real-time feedback on both energy balance and the proximal food and eating environment. The use of real-time feedback and visualizations on energy balance and environment will be tested in future studies to determine if they lead to behavior changes favorable to weight loss and control.

Development of BALANCE

The BALANCE tool features the MSB, which measures the type, amount, and location of physical activity in real time under free-living conditions by capturing a number of signals, including acceleration, barometric pressure, light, and geophysical location. Expanding upon earlier proof-of-principle studies demonstrating that the MSB could classify 10 different common physical movements with 95% accuracy,[19,20] we completed a study in which 53 participants performed a series of activities equipped with a MSB unit worn at the left hip under two conditions. In the laboratory, they walked and jogged on a treadmill over a range of speeds and elevations. In the field, they performed a series of activities under free-living conditions, including sitting, standing, walking on level and graded surfaces inside and outside of a building, riding up/down an elevator, and walking up/down a flight of stairs. The accuracy of the unit for classifying physical activity type and amount was established using the recorded activity ("labeled ground truth") as the standard and its associated energy expenditure against directly measured oxygen consumption using calorimetry as the standard. A portable calorimeter (Cosmed K4 b^2) was used in the field.

Our initial efforts focused on estimating speed of movement by determining step frequency from the accelerometry profile and estimated stride length from subject height. Although we were not able to measure grade changes during treadmill activity, we were able to detect movements that occured on a level or graded surface during the field experiments using the barometric pressure sensor output. Activity-based energy expenditure was estimated with activity type and subject body weight using either the American College of Sports Medicine's metabolic prediction equations[21] for major forms of human movement, including walking, jogging, stair climbing, and cycling, or, for other detected movements, the metabolic equivalent values (where 1 metabolic equivalent value is equal to 3.5 ml O_2/kg body weight^{-1}/min^{-1}) in the Compendium of Physical Activities.[22] Using this unique approach, MSB energy expenditure estimates were 89% accurate in the lab and 76% in the field. Importantly, the device performed significantly better during both conditions than a commercially available accelerometer that was also worn during the experiments. The technical details of the MSB were presented at UbiComp 2009.[23] The full study results were presented in part at the American College of Sports Medicine's 56th Annual Meeting (May 2009), and the final data are currently being prepared for publication.

Prototype

In year 1, using a list of design goals developed and refined over several months, we built a prototype food diary with energy balance visualization on a mobile phone and integrated it with the MSB via wireless Bluetooth connection. We reviewed currently available food consumption tracking programs to create a new and innovative food diary offering improved features and usability compared to available products.

The first version of the program was built using Python programming language on a Nokia S60 smartphone. The BALANCE tool consists of three major components: (1) a food diary allowing users to manually enter the type and amount of food and beverage consumed (**Figure 1A**), (2) an activity diary allowing users to see the list of activities "sensed" by the MSB (**Figure 1B**) and to manually enter activities the MSB cannot measure, and (3) the personal "fuel gauge" visualization, which computes and displays the difference between energy intake from electronic food entry and energy expenditure from the MSB and activity diary (**Figure 1C**). Because the MSB cannot measure all types of movements (e.g., water-based activities and those using primarily upper-body movements), we needed to build an activity diary into the mobile phone program so that subjects could manually enter specific "purposeful bouts" of activity to complement the continuous objective data being provided by the unit. Energy intake was estimated using food types and quantities entered in the food diary, based on the United States Department of Agriculture (USDA) National Nutrient Database for Standard Reference Release 20. The diary allows users to manually enter foods and beverages that are not in the database. Users can also enter the time of consumption, and each entry is automatically time stamped. A portion of the basal metabolic rate is "credited" to the user every hour based on the Harris–Benedict equation, a widely used, albeit imperfect, method for predicting metabolic rate.

Next, we performed an initial evaluation of the prototype by defining and entering specific meals, a combination of simple common foods, prepared foods, and some foods that were not in the USDA database that required manual entry of nutrient content. We experienced difficulties with the food diary, including a lack of availability and variety of ethnic and commercial foods, limited units to select for portion sizes (i.e., grams only), and programming limitations. This work provided early feedback for improving the food diary and the energy balance visualization.

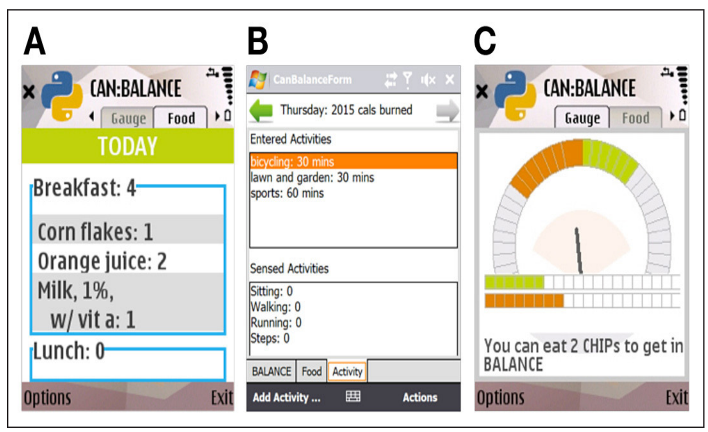

Figure 1. The BALANCE tool. The food diary is shown in **A**, the activity diary and sensed activities in **B**, and the personal "fuel gauge" in **C**. The left side of the visualization (orange) depicts energy expenditure and the right energy intake (green) expressed as CHiPs, or calorie hundred points, where one CHiP equals 100 calories rounded to the nearest half CHiP. The message displayed on the screen indicates that the user is currently in negative energy balance (energy expenditure exceeds intake) and can eat two CHiPs' worth of food (about 200 calories) and still be in energy balance. CHiPs accumulate on either side of the fuel gauge center as the user enters foods and beverages and expends energy in physical activity. A portion of the user's basal metabolic rate is "credited" as an energy expenditure CHiP every hour by partitioning the total by 24.

We also assembled an up-to-date geographic information system (GIS) database of King County, Washington, for linking types and amounts of measured physical activities and eating episodes with *XY* locations captured by the integrated global positioning system (GPS) receiver. The GIS and the mobile application program ArcPad work together to provide users with a visual display of food sources and their classification, and locations associated with physical activity, within their proximal environment (**Figure 2**). The GIS data were compiled from several data sets, including King County tax-lot-level and building-level assessor's files, Public Health—Seattle King County food permits, InfoUSA, and Washington State Department of Transportation roads. Land uses were classified into several categories commonly used in public health literature (e.g., generalized land uses, transportation infrastructure, parks and open spaces, supermarkets, fast-food restaurant, and fitness facilities). Other classifications include sources known to be associated with more walking, size of establishment (including number of seats provided), establishment belonging to a national or regional chain, and availability of alcohol, among others.

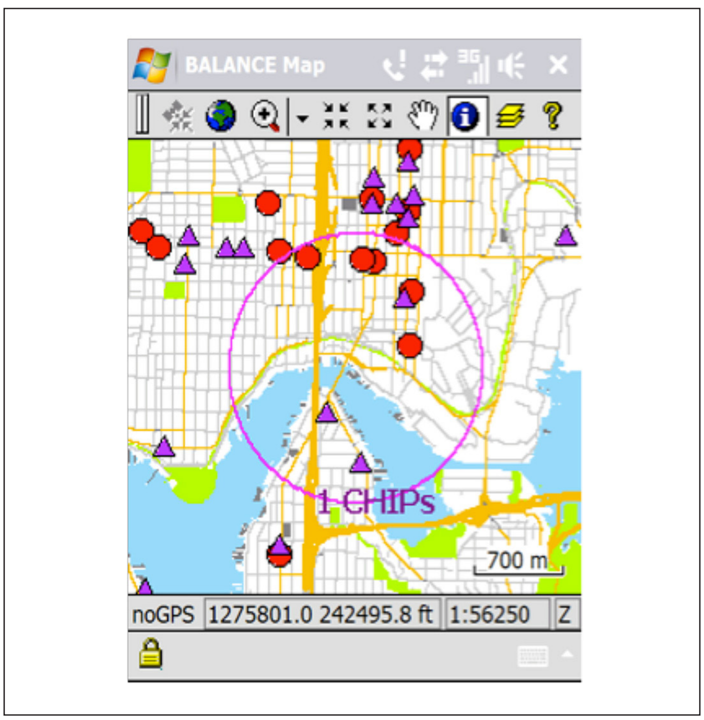

Figure 2. The activity and eating resource-mapping program. Red circles depict convenience stores and purple triangles bakeries/delis (eating locations), while green areas show public parks (activity locations). The user can obtain detailed information about a specific location by using the phone's keypad or cursor to highlight it. Sources in the 1 CHiP circle indicate locations within one km of the user's present location; walking to any of these locations would earn the user up to one CHiP.

Early in project year 2, we replaced the USDA database with the Nutritionist Pro Knowledge Base (Axxya Systems LLC, Stafford, TX). This database consists of over 32,000 foods and ingredients, including brand-name foods, fast foods, and ethnic foods. We also switched platforms to the HTC Fuze, a smartphone running Windows Mobile 6.1 Professional, because of its large touch screen, qwerty-type keypad, and more extensible operating system. Next, we completed a usability study of 12 participants that collected data on users' habits and preferences in order to inform software redesign. These participants were mostly young to middle-aged women (n = 9, 20–49 years) who were employed full time in a variety of professional fields. All had mobile phones and were well accustomed to using them. Results included users' level of interest in different software features and evaluation of various energy balance visualizations. The preferred visualization is shown in **Figure 1C**.

The Design Feedback Iterative Cycle

We are currently implementing a series of design/feedback cycles to test and refine the latest version of the food diary. Each cycle, designed to obtain both quantitative and qualitative data about user experience, consists of small focus groups of three to five subjects who use the phones for three days to enter their food and beverage intake. Subjects are between the ages of 18 and 65. There are no restrictions on any other demographic characteristics, although we are aiming for each focus group to include people with varying levels of technological skills. Quantitative data are obtained from two validated user experience questionnaires[24,25] and qualitative data from videotaped focus group sessions. These data will be analyzed to provide information for usability improvement. We anticipate five to six cycles of data collection before we reach a "final" version ready for validation in a larger sample. We have completed three focus groups to date, which have already provided valuable insight for system improvement.

Validation

As discussed previously, we validated the MSB unit in a concurrent study. In the upcoming project year 3, we will validate the BALANCE tool with its energy balance and environment-mapping features enabled using two approaches. In one experiment, subjects will complete an expanded, one-hour field test on the University of Washington campus and in the adjoining urban neighborhood while wearing a portable calorimeter and a Garmin GPS receiver, which provide criterion measures of energy expenditure and location to match against the tool's output. The test consists of an approximately three-mile loop of both level and graded walking (with some areas having greater than 10% slope), sitting, and standing. In another experiment, subjects will use the tool for three days to enter food and beverage consumption and specific physical activities not measured by the MSB while simultaneously completing a three-day food record and a physical activity questionnaire.

Summary and Future Directions

The major innovation of our technology is its ability to record peoples' movement and diet through space and time under free-living conditions and conveniently assist in the monitoring of energy balance. Subsequent research will focus on the use and evaluation of the tool in an intervention setting. For example, we will test whether providing information on energy balance and the proximal activity and food environments assists in behavior changes favorable to weight loss and/or weight maintenance. Ultimately, this work could lead to numerous health-related applications for practitioners, researchers, and consumers alike.

An important consideration for our work is that technology is rapidly changing. To keep pace with new innovations, our goal is to build a *program* that is portable to other platforms. Thus we do not feel limited by the platform, and in the future, we can change mobile phones as needed to be current with the latest technology. Furthermore, by addressing several design specification issues, the program can be customized to accommodate various end users.

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