Feasibility of Long-term Monitoring of Everyday Health Through Smartphones

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ABSTRACT
Primary healthcare suffers from the single feature, single point-in-time syndrome. Physicians need *long-term* data along multiple aspects of a patient's everyday health before, during and after treatment to best determine how the patient is doing. Smartphones present a scalable, easily deployable and cost-effective means for long-term monitoring of everyday health. Our work explores the importance of long-term monitoring of everyday health and proposes how smartphones can fulfill this task.

Categories and Subject Descriptors
H.1.2 [**User/Machine Systems**]: Human Factors; J.3 [**Life and Medical Sciences**]: Health

General Terms
Design, Experimentation, Human Factors, Measurement

Keywords
Everyday Health, Health Monitors, Smartphones

1. INTRODUCTION
Typically, our vital signs are measured only when we visit a primary care facility. Even when measured, they represent only a *snapshot* of our general health at that *moment alone* — failing to capture the continuous spectrum in our lives, i.e. our *everyday health*. Our general health is affected by our daily lifestyle choices. Without such measurements, primary care physicians/professionals (PCP) are limited in their ability to make informed and reliable recommendations toward improving our health. PCPs may interview us about our daily activities, but as human beings, we are notoriously bad at remembering, estimating and articulating *objectively* our levels of stress; how much we eat; how much we exercise; and how much we sleep. Worse, the longer the period of measurement, the poorer the accuracy of our recollection. Typical PCP visits only last about 20 minutes[11], limiting the opportunities for open conversations to separate important health incidents from otherwise unremarkable outliers.

Today's smartphones are already equipped with features that enable ordinary people to monitor and measure their everyday health along *multiple* aspects e.g. diet, fitness, stress and sleep. This approach leverages **readily available** smartphones and turns them into **inexpensive** health monitoring devices. The ubiquity of smartphones – 45.4 million users in the US alone[20] – allows this approach to scale to the general population, providing a means for primary care initiatives to reach millions.

There is already a proliferation of smartphone applications for health and fitness. Nonetheless, many applications merely use the smartphone as a logging device for manual entry or reference of information about health e.g. menstruation and chronic diseases e.g. diabetes. Such applications do not take advantage of common features such as camera, voice, GPS or accelerometer units on modern phones by Apple, Google or RIM (together accounting for 70% of the smartphone market[20]). These features provide innovative semiautomatic opportunities to monitor people's health.

Our work explores monitoring everyday health – beyond just chronic diseases – to help people maintain optimal health in a *proactive* rather than *reactive* manner through their smartphones. Such an approach heralds "an array of technology-enabled, consumer-based services that constitute a new form of primary health care"[26], the same vision espoused by Dr. David M. Lawrence, the former CEO of Kaiser Permanente, in the May 2010 Health Affairs special issue on *Reinventing Primary Care*.[25].

2. MONITORING EVERYDAY HEALTH
The World Health Organization (WHO) defines health as "the state of complete physical, mental and social well-being and **not merely the absence of disease or infirmity**" [34]. The Healthy People 2010 plan, the US government plan for promotion of health, states its primary goal as: "helping individuals of all ages increase life expectancy and improve their quality of life" [3]. While the healthcare system has made great advances in the treatment of diseases, less has been done to help improve everyday health in the population. It is considerably *harder* to monitor these broad aspects of daily living and their impact on short-term and long-term health. Long-term monitoring with smartphones can contribute by filling this niche in primary care.

We have selected the following **five** salient aspects to monitor for everyday health; the details of our proposed methodology are in Section 4.

Diet — Diets high in calories and fats can contribute to obesity, diabetes and heart diseases[32]; diets low in required nutrients can lead to malnutrition[22]. Additionally, the food consumed in conjunction with certain drugs can cause notable side-effects which might not otherwise be apparent. *Our approach takes advantage of the built-in camera, microphone and GPS to enable a multifaceted approach for calorie and nutrient estimations that makes use of photos, video, barcodes, voice prompts and location.*

Fitness — Adequate quantity and quality of exercise is vital for health. Sufficient exercise not only helps weight management but also reduces the risk of heart disease, diabetes, high blood pressure and other diseases[19, 17]. *Our approach estimates calories burned using the accelerometer unit for motion and the GPS unit for distance traveled.*

Stress — Studies show that high levels of stress have a direct impact on health[18, 33]. High levels of stress also contribute to obesity[9]. *Our approach estimates stress using voice (tone and pitch) and content (sentiment) analyses.*

Sleep — Insufficient durations of good quality sleep have been linked to a number of chronic diseases and conditions, including diabetes[24], cardiovascular disease[23] and obesity[31]. *Our approach uses the accelerometer unit to detect movements on the bed and estimate sleep quality from those movements.*

Life Events — Events such as menstruation, colds, challenges at work and vacations cannot be deduced from diet, fitness, stress or sleep alone. Such life events are important factors in everyday health and cannot be ignored. *Since it is hard to quantify all the different life events that can occur, it must be done in an open manner. The smartphone allows description of life events either through text or voice memos.*

While there are certainly other aspects that we could measure, based on our personal interviews with PCPs, these were the aspects that we concluded to be most relevant. Incidentally, these are the same aspects selected by the National Center for Integrative Biomedical Informatics (NCIBI)[5] at the University of Michigan for integrating longitudinal environmental phenotype data into patient electronic health records (EHR). Each aspect is vital and has clinical significance but only by considering **all of their interactions together** in an integrative approach can we foster a better understanding of everyday health.

3. USE CASES

To determine how such an approach could be useful for PCPs, we conducted several interviews. We summarize four below, illustrating the different use cases where long-term monitoring is valuable.

> [B]y making it easy to measure such things outside of the clinic opens new opportunities to study how patients are in **real life**. And while some of the monitoring and measurement devices that you use might lack clinical accuracy, that's fine since we are more interested in looking at the **trends** in how those values change ... we can always measure those values again using better medical equipment.
>
> – *Jens (Jay) Yambert, MD, FACP, FACEP*

> When I prescribe drugs for patients, I want to know its **effectiveness** and if they are experiencing any **side-effects**. For example, if their cholesterol goes up – is it due to the drugs or their eating habits? Ideally, I would like to know that to determine whether or not to adjust their treatment.
>
> – *Kimberly Smith, MD, MPH*

> Such a system could prove useful for **early assessment** and **treatment**. If a patient comes into the clinic with reliable data about her diet, fitness, sleep and stress, I might have a better idea on how to start her on the most appropriate treatment ....
>
> – *Evan Lyon, MD*

> The biggest contribution ... [is] for research in larger scale **cohort studies** than what we can do today. The data collected from such monitors would feed directly into models to study the correlations between diet, fitness, stress and sleep; and also to foster the study of correlations between such aspects and general health. Enabling such research *might* yield interesting results like the Framingham study [15] did; and in the future – not the short term – such results could be used directly for PCPs. *We wouldn't know until we try.*
>
> – *Steven Whitman, PhD*

Overall, PCPs were enthusiastic about such a system and could see themselves benefitting from it in their daily consultations in primary care. However, we acknowledge that before PCPs can use such a system, we must first demonstrate that it is feasible for people to monitor and measure their everyday health.

4. PROPOSED METHODOLOGY

We now describe how features of the smartphone enable it to function as a long-term health monitoring device. Some of the methodologies are our ideas that leverage existing research and have yet to be commercialized in applications; when commercial implementations exist, we explicitly mention them.

While we conjecture that the smartphone and its features are adequate to monitor our selected health aspects, work remains to evaluate the accuracy and precision of such approaches compared to other alternatives. We are working on implementing a full software package for our proposed methodology which will enable us to report on the error margin under typical scenarios. It is worth emphasizing that (i) PCPs are more interested in the trends of changes rather than the accuracy of a single reading and (ii) for many of these aspects, no cost-effective and deployable alternative currently exists for long-term monitoring so leveraging smartphones is an appealing option.

4.1 Monitoring Diet

Estimating the calories and nutrients consumed through meals is the *most* challenging health aspect to monitor. Various approaches have been attempted before. Manual procedures such as photo diaries capture what was eaten but fail to provide a record of nutritional value of the meal. Semi-automatic procedures using calorie counting software provide better estimates of nutritional value but require the user to go through the extensive database of ingredients in the software. The ubiquity of smartphones with cameras makes photography easy and accessible. Leveraging this, in Japan, Metaboinfo's Virtual Wife[8] has a team of nutritionists **manually** analyzing cellphone photos of dishes to provide instant calorie estimation for its users. Existing research [13][27] attempts to use **automated** computer vision techniques to estimate calories from food photos. Although promising, the performance has been limited. Variations caused by many factors such as distance and lighting conditions make *single* photos of meals poor candidates for reliable image processing. We have developed an approach that takes advantages of videos for dietary assessment and found videos to be more reliable[14].

Our review of the current technology demonstrates that there is no single fully automated way to estimate calories and nutritional values; *some* user interaction is still required. Therefore, we leverage multiple features to simplify the interactions:

Camera — The user captures photos or videos of her meal before eating it. The software uses computer vision technology to (i) estimate the size of the meal; (ii) recognize this meal based on an internal database; and (iii) store the photo or video of the meal for archival purposes. The internal database of meals is compiled from the videos of meals taken from various restaurants. When it fails to recognize a meal, it prompts the user to enter more information taking advantage of the health care bill that mandates chain restaurants to prominently display calorie counts whenever possible[10]. If the user is eating a prepackaged meal, she would photograph the barcode[1]. The software looks up the barcode from the open source Internet UPC database[4] (as of May 2010, it contains over 1.2 million entries) and extracts the calories and other nutritional information about that prepackaged meal – *Breadcrumb* and *FoodScanner* are applications that already support barcode scanning.

Voice — When it is not possible to recognize the meal visually, the software prompts the user to describe the meal through speech using simple sentence structure e.g. "a plate of spaghetti and meatballs". Using speech recognition technology, it recognizes keywords describing the meal and estimates the nutritional content from an internal database. Alternatively, when it is inconvenient to take a photo of the meal, the user can choose to invoke the voice system directly.

GPS — The built-in GPS unit provides valuable geographical location concerning where a person is consuming her meal. This helps identify the restaurant she is at to intelligently filter the possible types of food that can be ordered, greatly reducing the choices that our system has to look up to find the best match when using the camera and voice approaches.

Perfect accuracy, while desired, is not always necessary. PCPs are more interested in the trends and changes in their patients' calorie intake throughout the weeks and *relating* that with the amount of calories burned through exercise.

4.2 Monitoring Fitness

The software can use these features on the smartphone:

Accelerometer — The accelerometer unit detects motion in three dimensions; it can be used to estimate the number of steps taken and estimate calories burned while indoors (GPS doesn't work well indoors).

GPS — The built-in GPS unit provides geographical location of the user. Based on the velocity (estimated from change in GPS location over time) and motion from the accelerometers, the software can infer if the user is on a vehicle, cycling or walking. For each activity, it estimates the calories burned.

Commercial applications such as *RunKeeper Pro* and *Go Pedometer* already implement *some* of these ideas.

4.3 Monitoring Stress

The software can either intercept calls on the phone or require the user to read a simple paragraph of text that is displayed on the smartphone. The software first uses voice analysis to estimate stress levels[28]. Then we convert the speech to text and further perform *sentiment analysis*[29] on it to estimate stress. Sentiment analysis has been used to track trends in ordinary people's positive or negative opinion (sentiment) regarding particular drugs over time[12].

4.4 Monitoring Sleep

We use the accelerometer unit to determine sleep patterns. The user places the smartphone on the bed before going to sleep and the different movements on the bed as the user sleeps trigger the accelerometers in the phone. These movements have distinct patterns and can be used to detect sleep duration and phase. This approach has been used commercially in the *Sleep Cycle* application.

4.5 Monitoring Life Events

Measuring life events is akin to keeping an electronic diary. The software will (i) enable jotting down notes about life events either textually or through voice memos when an event occurs and (ii) periodically reminds the user to record events in case she forgets. Once per week, the smartphone application also prompts the subject: "Did anything notable happen last week?" The user has the opportunity to note events such as vacations, menstruation periods, colds, and challenges at work that cannot be deduced from her diet, fitness, stress or sleep alone.

5. SUBJECT ADHERENCE

Even with the importance of everyday health and the feasibility of using smartphones to monitor it, the question remains: *will ordinary people monitor themselves regularly?* There are two key reasons why smartphones would work well for health monitoring: transparency and connectivity.

By leveraging a device that millions already carry everyday, the act of monitoring is almost fully transparent. We carry our phones almost everywhere, allowing it to track our motion and exercise; we carry out conversations everyday, allowing it to monitor our stress levels; we sleep with our phones nearby, allowing it to detect our sleeping motion; and our phones are usually with us when we eat a meal. No other device is as ubiquitous and as well-suited for personal monitoring.

The smartphone allows us to stay connected to our social networks and social sites. There is a growing subculture of dieters and data-driven people who are habitually visualizing their food consumption on websites such as eat.ly. People are using websites such as PatientsLikeMe.com to share their experiences dealing with various medical conditions. Our approach taps into and can leverage this developing online phenomena. People are motivated to do this because their social networks provide support – engagement and encouragement – for them to maintain and improve their health[16]. *Instead of being a chore, it is rewarding for them to track their progress and see how they improve over time.*

6. BEYOND MONITORING: TOWARD MEASURING AND MANAGING

All the data collected can be integrated and visualized giving an *integrated* perspective of a person's health and how she is doing. The visualizations provide a powerful means for users to describe how their diet, fitness, stress and sleep change *with respect* to life events. Our system *quantifies* and displays them as a dynamic graph over time, allowing *objective* comparisons between different periods. The aspects we measure change daily, allowing comparisons in trends even between short periods of time.

The changing data provides opportunities to detect lifestyle patterns. Figure 1 shows the summary view of data for April 20, May 10 and May 11 respectively for a subject. The data is real but collected manually through interviews then mocked up using our visualization. The subject was having her take-home exams on May 10 and 11. The data on April 20 represents her typical day. By comparing the visualizations, we notice that during her exam days: she consumes more calories (longer blue bars), exercises less (shorter green bars), has higher levels of stress (higher stress overall) and had less deep sleep (less green bars and more orange bars). We interviewed her and discovered that she had been eating out because she did not feel like cooking. She was mostly sitting at her desk working on her exams. She was also up late working on her exams. Overall, she was feeling more stressed during these two days. This example shows how a life event i.e. take-home exams affected a change in the subject's lifestyle compared to her non-exam days. Such information can prove useful during a typical PCP visit.

Because such data is now recorded, in the future, it will allow more personalized forms of recommendations and treatments from PCPs based on a person's profile and history. Such data opens new research and medical opportunities for personalized health care.

7. RELATED WORK

Using smartphones for health and fitness is not a new idea. Smith has documented how smartphones can be used as effective devices to help manage chronic illnesses[30]. However, most approaches relegate the smartphone to the role of a hub (i.e. aggregating data from other high-precision devices) or a logger (i.e. entering data manually). Most approaches also tend to focus on managing chronic conditions and not everyday health. The *Personal Health Monitor*[6] in Australia enables the use of normal smartphones as a hub to track multiple readings (e.g. ECG, Oximeter, Blood Pressure, Weight, Blood Glucose) but focuses only on chronic conditions. *Project HealthDesign*[7] explores practical ways to capture and integrate patient-recorded observations of daily living (ODLs) into clinical care. *Project HealthDesign* is similar to our project because it realizes the untapped potential of ODLs to observe lifestyle aspects, and their impact on clinical care. Nonetheless, Project Health also focuses exclusively on chronic and clinical care not everyday health.

To the best of our knowledge, our approach is unique because it leverages the full features of smartphones to target everyday health. We differentiate ourselves by focusing on everyday health and not a specific chronic condition, believing that there is an untapped potential for discovering how our daily lifestyle choices affect our health both in the present and in the future.

8. DISCUSSION

In the future, it is likely that smartphones will serve as health monitors of multiple aspects. The ability to monitor a *subset* of our chosen health aspects is already available in two niche markets in Japan: the fragile elderly(built-in exercise monitor and healthy living diary)[2] and fashionable women(built-in pulse meter and exercise monitor)[21], focusing on chronic care and on weight management, respectively. Ideally, as the technology becomes available, all monitoring can be performed reliably using just a specialized cellphone that incorporates the best features from commercial health monitors. Long-term monitoring will be made easier requiring little to no interaction from the user.

Ultimately, we envision a system that can monitor, measure and manage a person's everyday health; such a system would suggest behavior modifications as necessary based on data collected from the population to promote healthy living and prevent health issues. In addition, accurate measurement can aid population stratification (clustering based on vectors of people's lifestyles), which will help provide different treatments for different persons in different cohorts.

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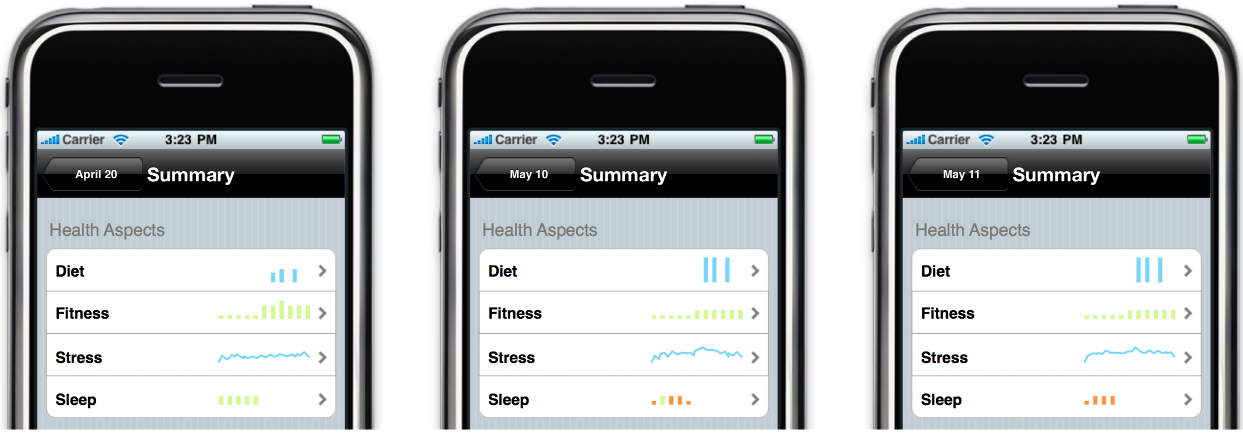

Figure 1: Actual data from one of our subjects mocked-up to illustrate how the aspects change in reaction to life events.

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