Reconfigurable, Wearable Sensors to Enable Long-Duration Circadian Biomedical Studies

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ABSTRACT

The last 10 years have seen the emergence of wearable personal health tracking devices as a mainstream industry; however, they remain limited by battery lifetime, specific sensor selection, and a market motivated by a focus on short-term fitness metrics (e.g., steps/day). This hampers the development of a potentially much broader application area based on optimization around biomedical theory for long-term diagnostic discovery. As new biometric sensors come online, the ideal platform enabling the gathering of long-term diagnostic data would have the built-in extensibility to allow testing of different sensor combinations in different research settings to discover what kinds of data can be most useful for specific biomedical applications. Here we present the first generation of a reconfigurable wrist-mounted sensor device measuring 7x4x2cm and weighing 51g with battery (29g without). In its current configuration, it has recorded skin temperature, acceleration, and light exposure; these three variables allow prediction of internal circadian rhythms, as an example of the application of biological theory to enhance pattern detection. This generation is capable of operating long-term with minimal day-to-day disruption via easily exchangeable batteries, and has enough space for several months of data sampling to gather long-term diagnostic metrics. Future developments will include the addition of energy scavenging and a wireless mesh network for ambient data collection, the combination of which will allow uninterrupted data to be gathered without depending on the user.

Categories and Subject Descriptors

J.2 [**Physical Sciences and Engineering**]: Electronics; J.3 [**Life and Medical Sciences**]: Medical information systems

Keywords

Biomedical monitoring, wearable sensors, biological rhythms, translational health metrics

1. INTRODUCTION

In the next several decades, medicine will mature from primarily intervention-focused to predictive and preventative. To accomplish this transformation, large amounts of potentially diagnostic biomedical data must be gathered across broad populations to enable the development of the predictive algorithms that will power early detection and disease avoidance in medical practice. Wearable devices could play a large role in generating these data, but to do so they must overcome hardware obstacles such as biosensor fidelity, battery life, and data accessibility. However, given the complexity of human physiological interactions with the modern environment and the role of these interactions as drivers for disease, greater difficulty may lie in discovering which data types provide the best long-term diagnostics for each medical condition in each different population. Outside of a biological framework, finding such patterns is reduced to a brute force approach. Therefore device development should be coupled with biological hypotheses to maximize efficiency of pattern discovery and validation, e.g., [18, 7, 5].

A central source of variance in biological systems is the presence of biological circadian rhythms. Circadian regulation is widespread in the human genome [13, 15], and diverse tissue systems show populations of cells with internal circadian clocks (see [14] for a review). As such, day-to-day shifts in circadian rhythms – such as those caused by artificial light at night, shift work, and jet lag – can disrupt the relative alignment of internal timing systems [4, 3, 8, 19, 24]. Such "internal desynchrony" interferes with biological processes and, when chronic, it increases the risk of many diseases, including heart attacks, cancer, obesity, depression, and reproductive dysfunction [16, 2, 1, 6, 22, 17]. In turn, disease states often show circadian symptoms, e.g., hormone concentrations might show changed waveforms; these fluctuations

BODYNETS 2014, September 29-October 01, London, Great Britain

DOI 10.4108/icst.bodynets.2014.257078

might not be apparent through daily one-time measurements but could be diagnostic when seen as changing daily waveforms, as has been shown for instance in adrenal hormones in circadian disrupted rats [23]. As such, using circadian biology as a starting framework for wearable device design has two advantages: in the short term, changes to daily waveforms of biological measures may assist assessment of current health state; in the long term, persistent measures of circadian stability will enhance the short-term projections and allow for the construction of personal predictive models of daily waveforms and rates of change thereto across time scales (e.g., changes in daily temperature rhythm across the female menstrual cycle, changes to blood sugar waveforms across season, etc.). By framing multivariate, high volume wearable device-generated data in biological time, the temporal resolution of data can be increased while the unexplained variance is reduced, and the probability of successful pattern detection for diagnostic purposes is increased substantially.

While biometric devices are in a state of rapid change, the ideal platform for interested innovators would be flexible so that new technological advances could be integrated to allow efficient evolution of biomedical device use. With such a platform, engineers could partner with biomedical researchers to efficiently integrate their specific advances into application hypothesis testing. This would speed turnaround of short-term payoffs such as instantaneous disease detection while sustaining the longer-term development of predictive diagnostic algorithms. For this platform to be capable of taking advantage of the predictable changes brought by circadian rhythms, it must be able to maintain high fidelity sensor input across several days.

In this manuscript we present a wristband device capable of continuous input from multiple sensors across more than 24 hours, with an easily exchangeable battery so that use is interrupted for only one minute/day. Internal circadian phase of core physiological functions can be predicted accurately with a combination of distal body temperature, activity, and light exposure [9, 10]. Therefore the platform presented here is equipped with a skin thermometer, accelerometers, and a light sensor, and gives output of these sensors across several days during real-world trials. This makes it viable to test biomedical hypotheses based on circadian waveform analysis. The platform is also designed to be flexible, allowing modular sensor configurations and user-reconfigurable recording parameters for modified tests as new sensor technology and biological hypotheses become available. Finally, this platform is being optimized to allow continuous, ambient data collection so that users can generate data capable of near real-time analysis without added user burden. It is our hope that the development of this and similar devices will speed the emergence of cheaper and more effective personal, predictive medicine through wearable device use.

2. DEVICE DESCRIPTION

2.1 Hardware

The device was designed to be highly reconfigurable while taking the shortest path to collecting data relevant to circadian biology. The core of the device is the NXP LPC2148 ARM7-based Sparkfun product “Logomatic V2” PCB. Starting with an off-the-shelf product kept initial costs and build time low and allowed quick replacement when damaged, as wearables often are. The board was also well-supported by the open-source hardware community which further reduced engineering time, though this work represents a significantly more advanced use of the board than ever previously attempted. The board was enhanced to include sensors to measure the three aforementioned analytes: distal body temperature, activity, and light exposure. Sensors and their interface circuits were chosen to be as simple as possible to enable an extremely low-cost circadian logger.

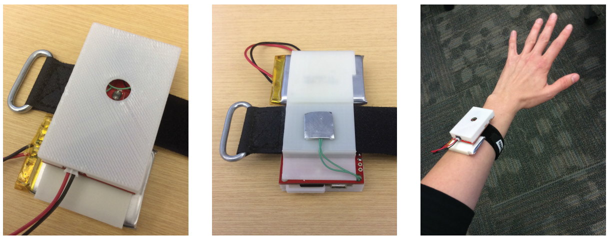
(a) Top (b) Bottom (c) Worn

Figure 1: Photos of current device showing light port (a), skin temperature plate (b), and device in use (c).

The PCB and sensors were combined with a 3D-printed enclosure, fastening strap, 2GB SD card, and 3.3V 1000mAh battery to form the complete device capable of logging several months of data (Fig. 1(a)). Its dimensions are approximately 7x4x2cm and it weighs 51g with battery (29g without), making it appropriate for comfortable wrist wear (Fig. 1(c)).

2.1.1 *Temperature*

A thermistor, TDK NTCG163JF103F, was attached to a thin 1.5x1.5cm aluminum plate with thermal epoxy and affixed with foam tape to the inside of the band. This was so the aluminum plate would make skin contact when worn (Fig. 1(b)). This provided maximum thermal conductance to the thermistor from the wearer’s skin while minimizing thermal sink to the rest of the device and ambient environment. The thermistor was wired as part of a resistive divider to one of the ADC ports on the PCB. The other resistor in the divider was chosen such that the thermistor’s 0.1°C resolution corresponded to the voltage of one LSB of the ADC over expected skin temperature range. This allowed power and part savings by eliminating the need for an amplifier. In the next iteration the sensor will be power gated by the microcontroller, allowing further power savings.

2.1.2 *Activity*

Activity was recorded by the MMA8452 triaxial digital accelerometer. Though all three axes were logged at the beginning, it was determined that any one of the three were sufficient to infer activity level. The axis horizontally perpendicular to the arm was chosen for analysis. Acceleration along other axes were ignored. Communication to the microcontroller took place over I2C when awake to measure instantaneous acceleration, or via interrupt signal during sleep to count all instances the device experienced acceleration beyond 0.1 g-force.

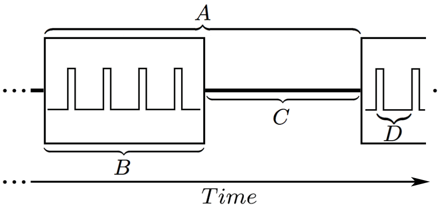

Figure 2: Data collection timing diagram. Each pulse represents one set of sensor data sampled and logged. Time A is the time between the start of each sampling block. Time B is the duration of each sampling block. Time C is the time spent outside of a sampling block, when the device is in sleep mode to conserve power. Time D is the time between samples. Times A, B, and D are all user-defined via an interactive Python script.

2.1.3 Light Exposure

The Clairex CL9P5L photoconductor was used to determine light exposure. It was attached to the surface of the device on the hypothesis that visible light reaching the wrist was a good approximation of the blue light entering the wearer's eye, stimulating the optic nerves that contribute to circadian rhythm maintenance. The data from this sensor needed only be qualitative to be useful, so the logarithmic response of the photoconductor didn't need to be linearized. Another resistive divider was built to roughly divide the range of the ADC into five brightness regions, which can be subjectively described as dark, dim, indoor night, indoor day, and full daylight. Like temperature, this sensor will also be power gated in the next iteration.

2.2 Firmware

The firmware included with the ARM7 board was augmented to include I2C support, sleep mode, interrupts, custom data logging formats, and adjustable sampling periods. Using a config file on the SD card, users can set sampling frequency, duration of sampling set, and length of sleep before another sample set (Fig. 2). While sampling, ADC values for temperature and light are taken and the accelerometer is queried. While sleeping, temperature and light are ignored but any activity that generates an acceleration greater than 0.1 g-force sends and interrupt to the microcontroller to increment a counter.

2.3 Software

Configuration and processing code was written to ease use of the device by biomedical researchers. The firmware config file is generated by answering questions posed by an interactive Python script, adjusting the variables described in Fig. 2 to suit the needs of the investigation. The resultant data files are also pre-processed by a Python script and then analyzed with Matlab code written to correctly interpret recorded data into useful results.

3. DATA

Initially data from each sensor was taken individually and used to calibrate or correct artifacts arising from the sensors themselves or their integration in the central board. All three sensors saw revision of data processing and output.

3.1 Temperature

The temperature sensor was designed to provide accuracy greater than clinical thermometers in use today but was initially found to undergo significant drift. A more stable voltage reference was built around the sensor to improve stability, only to find the drift's direction, but not magnitude, was changed. Despite this small but detectable drift, the relative temperature values during each sampling block clearly still capture diurnal rhythms. The overwhelming of the observed drift by the subject's daily temperature rhythm indicates this sensor is still applicable to circadian studies.

3.2 Activity

The accelerometer installed in this device is capable of capturing both greater temporal resolution and greater dimension depth than was deemed necessary for the application of the device to discerning circadian phase. Circadian studies traditionally rely on gross measures of locomotor activity, such as 10 minute bins of acceleration counts across the day. Initially the device revealed foot steps and hand motions, but the accelerometer's output was pared down to mere 1-dimensional counts. This generated savings of storage space and power while not impacting the biological application. This choice is an example of the kinds of optimization possible when device development is coupled to a specific biological framework.

3.3 Light Exposure

Early tests with the light sensor confirmed our ability to see consistent logarithmic changes in resistance with light intensity as expected. Repeated measures outside under noontime sun, inside under fluorescent laboratory lighting with and without daylight nearby, inside under low light, and concealed in a dark box allowed for the designation of consistent resistance ranges to different common lighting conditions. Although quality (e.g., wavelength decomposition) of light is not a feature of this device, the greater intensity of daylight than office lighting, and regressions against known sunrise-sunset times allow confident disambiguation of most light sources (i.e., the light intensity at all but sunrise and sunset may be enough to infer the source of light as artificial or natural in most circumstances; the presence of smooth transition curves under natural light at sunrise and sunset further help differentiate the source of light at those times, when intensity alone is insufficient).

3.4 Combined Measures in the Real World

Once all three sensors had been calibrated and artifacts corrected, a series of field tests was run. A representative sample of data taken by the device is shown in Fig. 3. In this example, the device was operated in the real world for 54 hours continuously, stopping only to briefly exchange batteries. It was configured such that all three sensors were sampled 10 times/second for 15 minutes, the system went into deep sleep for 45 minutes, then woke up to perform another 15 minute, 10Hz cycle. The sampling configuration was the result of prior tests run by the authors. These data span multiple sleep and wake cycles and persist through many kinds of physical daily activity. For this recording session subject was at home with exposure to natural and artificial light. The data show clear diurnal trends consistent across sensors, indicating that the device is likely suitable for circadian biology studies. Note for example the smooth rise in

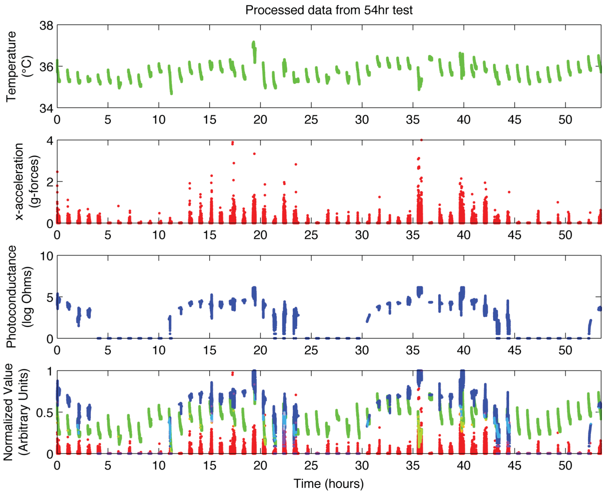

Figure 3: 54 hours of continuous recording shows predictable changes in temperature, activity, and light across three nights and two days. A normalized, combined overlay is also provided. Note that time to change batteries in not apparent in the data.

light intensity at times of sunrise, and the smooth decline at times of sunset, which transition into a plateau of artificial light into the evening on both nights, with decreased activity, validated by the self-reported sedentary evening actions of the subject (e.g., "watching a movie"). Despite a known error of ∼1°C thermistor drift over each 15 minute period – the source of which is under investigation – the diurnal cycle of temperature is still visually apparent, so circadian studies may not be affected. Future analysis will enable further refinement of the quantity of data taken, extending device capability and lifetime.

4. FUTURE WORK

For the entire history of life, availability of sunlight has shaped the evolution of behavioral "temporal niches" (e.g., diurnality in humans) and been the most reliable marker of seasonal change. Therefore, biological visual systems evolved to enable both image formation (i.e., seeing) and correctly timed daily and seasonal biological changes (e.g., increasing fat mass in shortening days). The integration of electric lights into modern life therefore disrupt biological timekeeping mechanisms. For this reason, the current urban environment presents a number of challenges to human health, such as shift work or light exposure at night, discussed in the introduction. Over a lifetime, such disruptions increase the likelihood of disease in every organ system, from cancer to arthritis to depression. However, the manifestation of circadian rhythms and the impact of artificial circadian disruptions are different in different people. Though the reality of negative health impacts from circadian disruption is now clear, studies in modern populations to identify best practices for different demographics (or individuals) are blocked by a lack of accessible data. Wearables provide a non-invasive mechanism of gathering such data, but are most useful only if researchers can configure the kinds of data acquired based on knowledge of biological systems. Thus the wrist band we present here is useful for those interested in studying circadian disruptions in people living freely in their environments. Our device requires only one minute per day to change the battery and upload data. This means that as a medical device it is unobtrusive, and could realistically be used to generate accurate weekly logs of individuals' activity cycles in the context of light exposure, precise in both time and intensity.

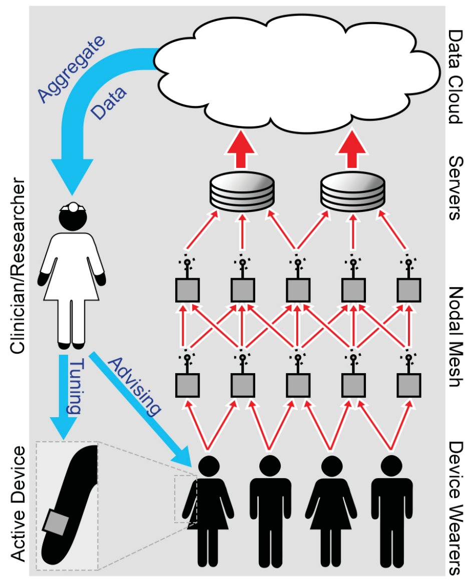

Figure 4: Conceptualized ambient network to collect and process wearable health monitor data.

For broader use (years of recording and/or accessibility to young children or the technically disinclined) user burden would ideally be negligible. Therefore the device presented here is also the starting point for a second generation device able to gather circadian data over long periods without user input or maintenance. Specifically, the future version of the wearable presented here is currently being developed as a fully-integrated wireless sensor system in the spirit of the Smart Dust mote concept [20]. This device will be small enough to be worn unobtrusively and use thermal gradient, kinetic, and solar scavengers to obtain power and perform sensing relevant to circadian biology. It will also take advantage of a data network utilizing existing work in wireless body-area networks (WBANs) [12, 11], and mesh networks [21]. A conceptual network layout is given in Fig. 4. These features would allow continuous monitoring without depending on the user to remember to recharge or protect the device, or to sync data. As such, this next generation will expand the current functionality presented here to enable continuous data gathering from each user. This will maximize the potential to identify patterns and provide diagnostics for long term ailments arising from lifetimes of exposure to the modern, disrupted circadian environment.

5. CONCLUSIONS

A reconfigurable wearable device founded in circadian biology has been presented. It is capable of logging skin temperature, activity level, and ambient illumination for an extended period. Its flexible nature allows the user to change sensors and adjust sampling behavior to more accurately tune the device's output for a given study. Results from our experience and biomedical researcher feedback continue to inform device refinements; we aim to eventually have an integrated yet configurable platform optimally targeted toward early detection and prevention of disease states in ways not currently feasible with wearable devices.

6. ACKNOWLEDGMENTS

This work was supported by the Department of Defense (DoD) through the National Defense Science & Engineering Graduate Fellowship (NDSEG) Program, and through the Berkeley Sensor & Actuator Center (BSAC).

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