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促進健康應用發展之具彈性及可擴充性之穿戴式平台
A Flexible and Extensible Wearable Platform to Promote Health Applications

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Abstract

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Chapter 2

Background and Related Work

In this chapter, we begin by surveying the wearable devices for healthcare applications on the market today. Then, we describe the modern ways that target to rapidly prototype wearable applications. The next section describes the works which build the customized device for their wearable applications. In the last section, we explore the potential design concept to enhance the process of rapid prototyping with flexible and extensible.

2.1 Wearable Devices with Healthcare Applications

Recently, a great number of commercial products leverage mobile, sensing and wearable technology to promote people's health in daily life. The smart phone is the versatile and most popular device in everyone's life. The smart phone can be used to sense the vital sign along without additional external sensors. For example, Instant Heart Rate[1] is a phone application that uses the camera and flashlight on the backside of a phone to sense the heart rate. Strava[2] is a phone application that focuses on quantitating the performance of running and cycling exercises using GPS sensor. It also can work with external sensors, including wearable heart rate sensor and/or cycling sensors, to collect more detail information for further analyzing exercise event.

The wearable devices can not only be an extension of the smart phone but also can work

[1] Instant Heart Rate http://www.azumio.com/apps/heart-rate/
[2] Strava http://www.strava.com/

standalone for healthcare applications. Thus, it can reduce the burden of carrying inconvenient device by people and make computing even pervasive. A variety of wearable products successfully immerse in people's daily life in recent years. Wristband is the most common form factor in wearable devices. For example, the Fitbit[3] is a popular wristband device that can help people to better understand his/her physical activity. The Apple watch[4] and the Android wear[5] further enrich potential healthcare application on people's wrist with watch form factor. Much more wearable devices with other form factors introduce many novel applications to promote health. For examples, Under Armour[6] releases a sensor-embedded running shoe that can track and collect running metrics. Athos[7] is a smart apparel that monitors muscle activities and heart rate to assist training and exercise. X2 xGuard[8][3] is a product that embeds sensors to a mouth guard for tracking athletes accumulated head impacts during participation in contact sports.

Those emerging commercial products reveal the practical applications with wearable devices and smart phone for sensing human's activity, biosignals and monitoring health status. The forecast for wearable devices worldwide from Gartner[7] shows that the market of healthcare applications with wearable device is strongly growing in near future. In addition to develop a fantastic technology, the usability is also a key factor to the consequence of a design for wearable application. Because wearable application is highly interactive with human. A proper design process is necessary to result an ideal design that will be accepted by people. However, the design process between ideate, prototype and test typically will undergo many iterations before the design goal is achieved.

2.2 Rapid Prototyping for Wearable Applications

The iterative design[17, 20, 22] between ideate, prototype and test is the most costly part in the entire design process. The key challenge here is how to rapid prototyping in iter-

[3] Fitbit http://www.fitbit.com
[4] Apple Watch http://www.apple.com/watch/
[5] Android wear http://www.android.com/wear/
[6] Under Armour http://www.underarmour.com/
[7] Athos http://www.liveathos.com/
[8] X2 Biosystems http://www.x2biosystems.com/

ative design. In addition to product developers, academic researchers also have a great demand of seeking an efficient way to speed up the prototyping process. For achieving the design goal, several options can be adopted in different iteration in the design process. At the beginning of the iterative design, a low-fidelity prototype[23] is the ideal tool to rapidly examine the feasibility, check the usability and refine the ideal with minimum cost of building prototype. However, low-fidelity prototype may not be able to test the functionality on certain aspects. For example, we attempted to develop a wearable oral sensory system that recognizes human oral activities related to health[11]. For examining its feasibility, it requires building a wearable device integrated with the sensor. Therefore, people always demand a useful tool that contains electronic and/or mechanical components in the design process. In the subsequent subsections, we describe the related works of rapid prototyping for wearable applications.

2.2.1 Integrated Design Devices

Developers, designer and researchers would like to develop a wearable application with uncomplicated process and without significant engineering skill to work with it, such as wiring, soldering, coding and so on. For non-engineering background users, an off-the-shelf device would be a better choice. For examples, activPAL[9] equips motion sensor and storage for collecting human's physical activity. Shimmer[10] is a device that integrates various types of sensors, storage, wireless connectivity and software for accessing the device. The Mercury [12] is an example that uses Shimmer in their study for high-fidelity motion analysis of patients being treated for neuromotor disorders. The HealthPatch[11] is a bandage-like wearable device that embedded ECG sensor, accelerometer and temperature sensor to track human's health. Smart phone is also a versatile device that integrated many sensors. Eric C. Larson et.al.[10] leverage the microphone on the smart phone carried in shirt pocket or using a neck strap for preserving the cough activity. But a fixed design can only offer limited functionalities and meet the needs of limited applications. Once the user

[9] activPAL http://www.paltechnologies.com/
[10] Shimmer http://www.shimmersensing.com/
[11] vitalconnect http://www.vitalconnect.com/

need an extra function or different form factor, it can not satisfy the need of developing new application and service. Thus, the people may be willing to pay more cost and effort for better prototyping their design.

2.2.2 Prototyping platforms

Several tools can help people to easily prototype a device for developing and testing a design. For example, the Arduino[12] is an open-source platform that provides easy-to-use hardware and software for making electronic device. It also has the version, e.g.: Arduino Gemma, that targets the user for developing wearable application. Arduino is a successful platform that you can easily get many resources to prototype your idea including plenty of compatible sensors, actuators, feedback components and software libraries. After the device is constructed by the Arduino, it is not that robust in use due to its wiring mechanism for connecting components. The Intel Edison[13] presents a development kit that offers high computational performance and wireless connectivities including Wi-Fi and Bluetooth. Through a breakout board, it can connect other components as well as the Arduino. The Xadow[14] is another platform which is similar to Arduino. It adopts a well-defined connector and cable to simplify the process of connecting the components. Thus, the user is not necessary to worry about the wiring for connecting components in pin-to-pin fashion and the robustness of those wires.

2.3 Customization in HCI

After several iterations of prototyping a system of the wearable application in low-fidelity and medium-fidelity prototypes, the next step is to build a high-fidelity prototype for conducting a field trial and further refine the design. In product development, the implementation of the wearable system will involve with a great cost and effort in customization before launching the application and service to the market.

[12] Arduino http://www.arduino.cc/
[13] Intel Edison http://www.intel.com/content/www/us/en/do-it-yourself/edison.html
[14] Seeed studio http://www.seeedstudio.com/

Many HCI studies also customize their wearable system in order to have a workable and robust device used in field trial or to better demonstrate their design and concept. In our study, we implement a sensor-embedded teeth[11] to demonstrate the feasibility of sensing humans's oral activities with in-mouth sensor. As a proof-of-concept system, the effort of customization is relatively low. In this study, we have yet to place a Bluetooth radio on this oral sensory unit; therefore, thin wires are used to connect the sensor board to an external data-logging device for data retrieval and power. In our other study, the KetDiary[25] is a phone-based support system to enable the self-monitoring of ketamine use by recovering patients after returning to everyday life. We build a saliva-screening device to determine patient's ketamine use. The microcontroller triggers the camera module to capture images of the reaction zone of the test strip. When the microcontroller receives an image from the camera, a Bluetooth Low Energy (BLE) radio is used to transmit images to the patient′ s smartphone. A phone app is built on Android platform to enable the self-monitoring and progress visualization. Although, the implementation in the KetDiary is a mobile device rather than a wearable device, but this project shows that it required a lot of effort and significant engineering skill to build the system in order to use the device for a three-week study involving three ketamine-dependent patients. The mPuff[2] introduces a chest-worn device for detecting smoking behavior using motion, heart rate, respiration and galvanic skin response sensors. The MARS[14] customizes wearable devices with inertial sensors to recognize whole body movement. However, a number of studies for wearable application[2, 9, 14, 19, 13, 12, 24] use common components in their devices. A good wearable platform may be able to facilitate the process of rapid prototyping in such research projects.

2.4 Modular Design: Flexible and Extensible

Modular design is a design concept that separates each functional partition of the system as a module and standardizes the communication interface between modules to enable flexibility and extensibility. Each modules can be reuse to reduce the cost in customization. A modularized system can easily add new functionality without re-design entire system to shorten developing process.

Google Ara[15] and LG G5[16] are the flexible and extensible smart phones that allows users to make the choice of modules for build a smart phone as their need. The Nascent[17] allows users to build an electronic device using modular components such as speaker, inertial sensor and microphone, which has a similar quality to a commercial product. Recently, modular design also emerged in wearable area. The Vigekwear[18] is a developing kit that offers micro and modularized components including BLE microcontroler, inertial sensors, temperature sensor, barometer, heart rate sensor and OLED display. This developing kit aims for allowing users to develop a application on the wrist. The BLOCKS[19] is a modular smartwatch that lets users to tailor the features as they needed. It contains several modules that can function on the wrist, such as temperature sensor, ECG, GPS, camera, NFC, gesture control an so on.

The concept has been widely explored in product manufacturing to discuss the tradeoff between modular design integrated design[18, 21]. In addition to making a modular design in manufacturing phase, i.e., each component is modularized physically, modularization also can be done in design phase. For example, the Altium Designer[20] is a PCB design software that can encapsulate a part of circuit as a module. Thus, the designer can rearrange the module to create different configurations and variants. Those examples shows that the modular design can be a useful concept to benefit rapid prototyping for developing wearable applications.

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[15] Google Ara http://www.projectara.com/

[16] LG G5 http://www.lg.com/us/mobile-phones/g5

[17] Nascent http://www.nascentobjects.com/

[18] Vigekwear http://www.giayee.com/bluetooth-bracelet/

[19] BLOCKS http://www.chooseblocks.com/

[20] Altium Designer http://www.altium.com/altium-designer/

Chapter 3

Design Exploration

The first step of iterative design for a wearable sensing platform is to understand the needs of potential users. We conducted two focus groups and two participatory design workshops to explore the needs from healthcare professionals.

3.1 Focus Groups

We performed two focus groups to better understand practical needs of wearable technology in clinical. In first focus group, we recruited four nursing professionals and two physical therapists from National Taiwan University Hospital. In second focus group, we recruited four nursing professionals from Taipei City Psychiatric Center (TCPC).

3.1.1 Participants

In first focus group, we recruited four healthcare workers (four experienced nursing experts and two physiotherapists), aged from 27 to 46 years. The four experienced nursing experts had worked as registered nurses for more than three years and the two physiotherapists have been worked in the Rehabilitation Department of National Taiwan University Hospital at least six years. Those participants were experienced in divisions of oncology, cardiology, and orthopedics. Four experts in second focus group, aged from 35 to 45 years, had worked as registered nurses for more than ten years at the Taipei City Psychiatric Center (TCPC) and specialized in providing inpatient psychiatric care for children, adolescents, geriatrics, and patients with substance abuse.

3.1.2 Procedures

The moderator of the focus group was a researcher with a background in engineering. After explaining the objective of the focus group, we provide five mock-up wearable devices with different form factors to encourage the participants to hands on. Then the moderator asked their perceptions regarding the usability, safety, and potential applications of those form factors. The second topic of the focus group is to encourage a story of the clinical scenario that can reveal any information derived from wearable device can benefit a healthcare application.

3.2 Participatory Design Workshops

We conducted the study to examine opportunities and constrains concerning the use of sensing technology, including wearable and environmental sensing technologies in healthcare applications. Following the participatory design process [8, 16], two workshops were held to co-design devices to assist healthcare workers in designing a wearable sensing platform.

3.2.1 Participants

Eight nursing professionals (four experienced nursing experts and four senior nursing school students), aged from 22 to 46 years, with experience in clinical nursing, were recruited. The four experienced nursing experts had worked as registered nurses for at least seven years and the four senior nursing school students had been nursing interns in hospitals for at least half a year. All participants were experienced in nursing patients in multiple medical divisions, with the main specialty spanning in divisions of oncology, pediatrics, cardiology, and orthopedics.

3.2.2 Prior to a Workshop

The nursing professionals were briefly introduced to the goal of this study and the structure of the workshop several days (about four to six days) prior to the workshop. Before attending the workshop, the participants were asked to finish the pre-workshop homework just as "homework" was assigned to participants prior to each workshop in the PICTIVE project [15]. This pre-workshop homework involved a design sheet to help participants describe and/or sketch five potential ideas for designs of devices that used any related wearable sensing technology to assist them in resolving difficulties that they faced at work or in their daily life. Since the purpose of this pre-workshop homework was to encourage the participants to generate a wide range of designs in the workshop, the participants were not asked to evaluate the feasibility of their prototype devices for solving the described problems or to limit them in their focus on post-operative caring scenarios. This pre-workshop homework helped the participants to brainstorm a wide range of ideas and collect observations from their working or everyday life as a warm-up for the upcoming workshop.

3.2.3 Procedures

A workshop comprised three sessions, which were (1) an engagement session, (2) a guiding session, and (3) a development session. Two participatory design workshops were held on two separate days. Each workshop lasted approximately four hours, including a half-an-hour break for lunch.

Engagement session:

In the engagement session (which lasted for half of an hour), all participants introduced themselves and presented the five design ideas that they had prepared for their pre-workshop homework. While presenting a design idea, each participant stuck a design note that also described the idea on a white board. Researchers generated appropriate categories and grouped similar ideas as the participants were placing their notes. After all of the notes on the white board, researchers and participants discussed and moved the notes among categories or to a new category using the affinity diagramming method. All of the categories indicate potential directions or building blocks in the development of the solution in the final design of the workshop.

Guiding session:

In the guiding session (which lasted for half of an hour), a moderator, who was a researcher with an engineering background, introduced the sensing technologies or projects related to healthcare applications. The purpose of the workshop was explained to participants, which was to use wearable and/or environmental sensing technologies in the design of devices that can help healthcare workers in caring for post-operative patients in hospital.

Development session:

In the final developing session (which lasted two and a half hours), four participants were separated into two pairs in which each participant could share design opinions. To stir cross-disciplinary thinking within each pair, one researcher with an engineering background helped participants to identify alternative sensing technologies for use in their design work and another researcher with a background in industrial and commercial design expressed their design scenarios using concrete storyboards. Consistent with the work-oriented participatory design process, the goal of each design was set, which was to help health care workers care for patients in hospitals. To assist the participants in performing the design task effectively, an A3 sheet of paper with the following fields was provided; name of their solution, target user, needs of the target user, targeted sensing events and required feedback, form factor of the designed device. The first stage of the development session involved the participants discussing the name and target user of the designed solution using categories that were obtained from the pre-workshop homework. Following the identification of the target users, the second stage involved determining the potential needs of the target user that are associated with the solution. In the third stage, the engineering researcher discussed with participants the selection of sensors and actuators for detecting targeted events or generating the required feedback in each application scenario. When the group completed its final design, the designer cooperated with the participants to finalize the form factor of the designed device by sketching an appropriate storyboard.

In the final stage, each group presented their final design, about which all participants discussed and commented.

3.3 Findings form Explorative Studies

In order to collect every experience sharing, perspective and interaction in discussion for further analysis, the audio recordings of focus groups and the video recordings of the participatory design workshops were transcribed and coded for key findings by researchers. All finding of design exploration for developing a wearable sensing platform are summarized as follows.

Form factor:

Several wearable form factors are discussed to identify what are the nice characteristics as a wearable device, including wristband, neckband, sticker, bandage, badge, garment, flip flop, strap and so on. The explored characteristics include easy wearing, taking off, compact and comfortable. The device should be comfort to wear and quick to deploy. The device also can be placed on proper body location to sense physiological data.

Flexibility:

Because there are various types of physiological sensors that can be used to develop different healthcare applications, a fixed design can only to offer limited functions on a device. It is difficult to have one single design that can fit all requirements to develop healthcare application. Therefore, if a wearable sensing platform has flexibility that developers can build a wearable device with required sensing abilities. Then, developers can use this device as a prototype to test their tailored healthcare application. In different iterations of design process, a platform with flexibility can easily deal with the situation that developers may need to add or remove functions on the wearable device.

Extensibility:

A wearable sensing platform must be easily extend and upgrade its abilities. In terms of the hardware part, the platform must be able extend new component without re-design entire system. In terms of the software part, the platform must provide comprehensive APIs to allow users to construct new method, function and algorithm on top of existing components.

Sensing and data:

To develop a healthcare application, several types of common information are collected using wearable device, such as vital sign, physical activity and so on. Since a wearable device collects sensory data, the next step is to process the data. Then, the system can feedback the processed data to corresponding users depending on their requirement. The platform should provide a meaningful representation of data that can be understood by the user, e.g.: a pedometer shows step count rather than raw data of motion sensor.

Configuration:

The complexity of configuration is a key whether a user will adopt a platform for development or not. In terms of non-engineering background users, they desire there is no complex steps to configure the device and the components are plug and play.

Battery life:

The work period of the wearable device is a critical concern for a healthcare application. The device must be able to survive until its mission is complete. A proper power saving mechanism can prolong the work period of the wearable device as long as possible and can work transparently to the user without complex configuration.

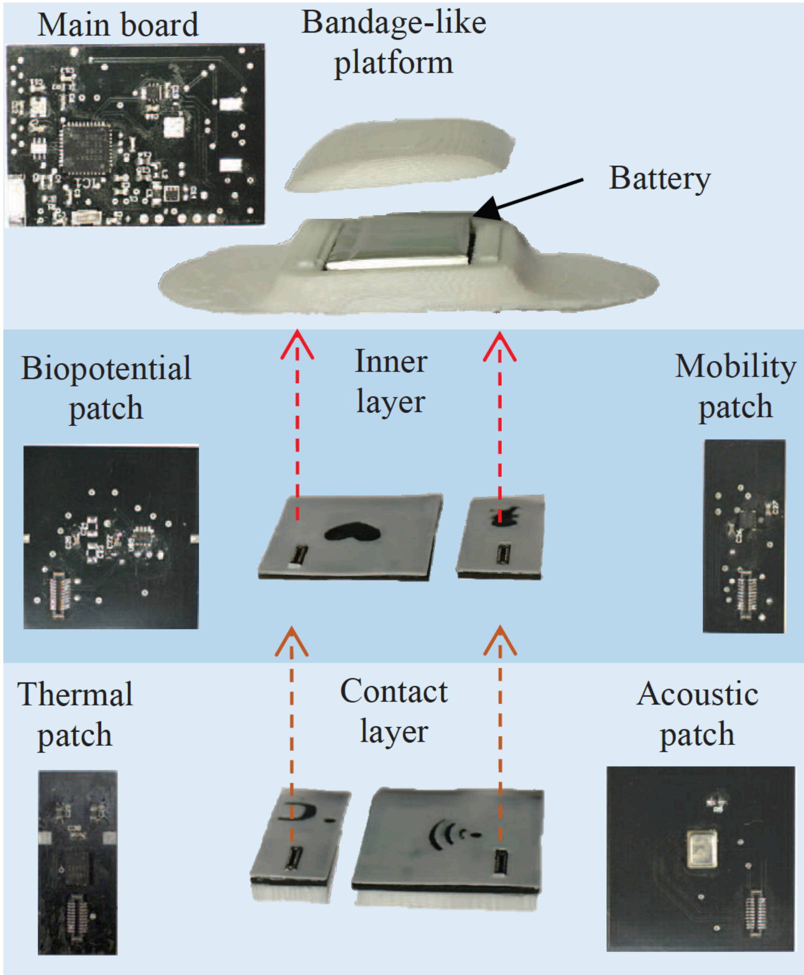
Chapter 4

BioScope: a Flexible and Extensible Wearable Platform

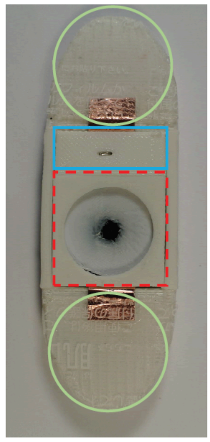
This chapter presents the design and implementation of BioScope, a flexible and extensible wearable platform for rapidly prototyping healthcare applications. BioScope is an extensible bandage system with components that can be stacked like Lego blocks. Using this system, users can simultaneously collect the four most commonly monitored biosignals (i.e., heart rate, body temperature, acoustic signals emitted from the body, and inertial readings of human movement) from multiple bandages to assess and diagnose physical conditions. BioScope extracts the processing and communication functions into a core building block, and hosts the required sensors. Each sensor is affixed as a patch that collects one biosignal. By stacking the required sensors onto a bandage-like platform, users can easily create a customized bandage that can be affixed to the skin of the patient. The data collected by the sensors are sent through a Bluetooth interface to the device screen used by the healthcare worker.

4.1 BioScope System Design and Implementation

Based on the design considerations, we designed and implemented the BioScope system. The following subsections include (1) flexible and extensible sensing bandage, (2) stacking mechanism, (3) sensor patches, (4) explorative experiment.



(a) Assembled circuit boards and bandage stacking



(b) Back view of a stacked bandage

Figure 4.1: Design of the extensible sensing bandage. (a) Four patches with distinctive embossed icons are stacked on the inner and contact layers according to the direction indicated by the red dotted arrows. (b) The sound-collecting structure (box with red dashed border), a thermocouple wire (box with blue solid border), and two electrodes coated with a conductive gel (two green circles) directly contact the skin.

4.1.1 Flexible and Extensible Sensing Bandage

To create an extensible system, we designed a device with two distinct modules (Figure 4.1): (1) the basic bandage platform and (2) sensor patches. The bandage-like platform resembles an adhesive bandage. We drew a 3D model of the platform and then printed it using a 3D printer and elastic filaments. Figure 4.1(a) depicts the platform, in which a hollow space is reserved to encase the customized sensing patches. To provide processing and communication capabilities, we designed a customized circuit board, called the main board, that could be mounted in the hollow space. The main board and the stacked sensor patches are powered by a 130-mAh Li-ion battery situated in the upper layer of the platform. On the main board, a Microchip PIC32MX150 microcontroller receives data from the sensor patches through board-to-board connectors, and then relays the processed data to the monitoring screen through a Texas Instruments CC2451 Bluetooth module.

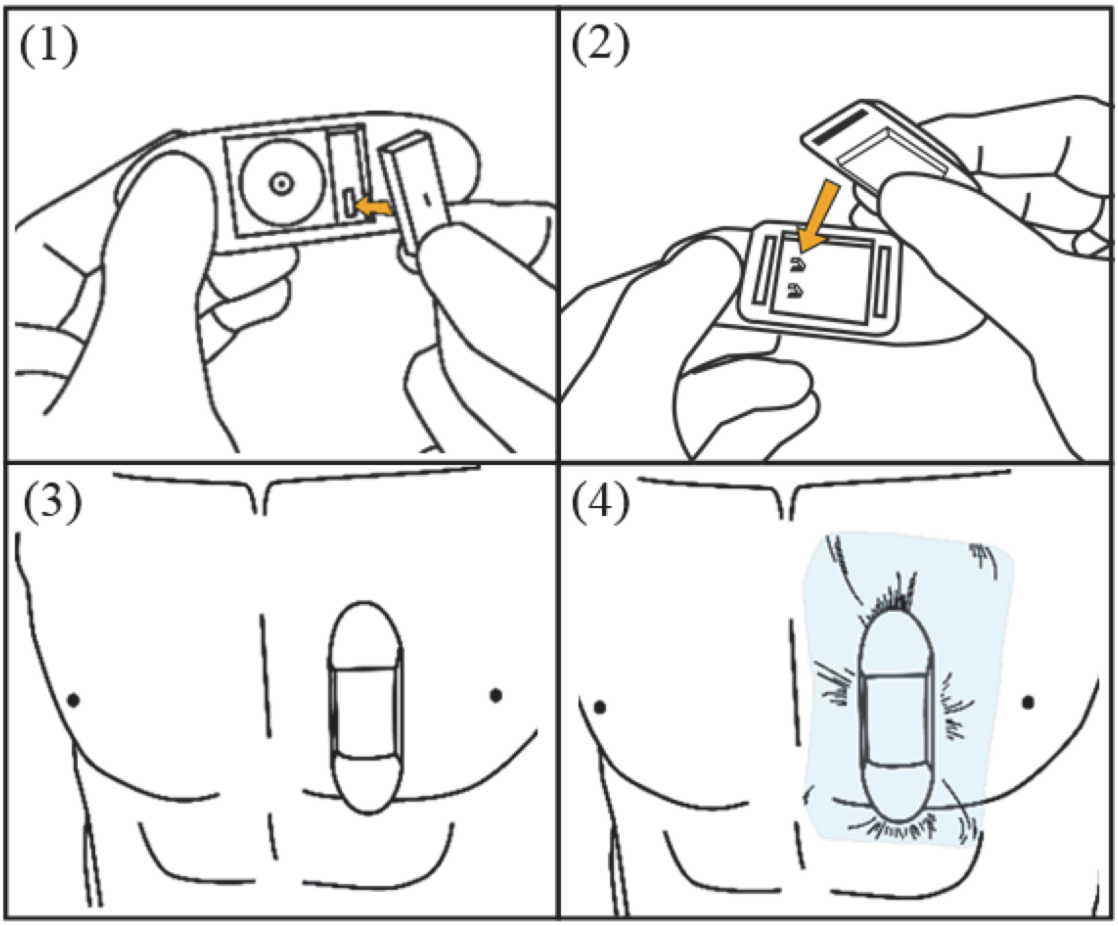


Figure 4.2: Four steps for applying bandages.

4.1.2 Stacking Mechanism

Users can choose different combinations of LEGO-like sensing and interaction blocks and assemble them inside a bandage form factor. This subsection describes the three main parts in stacking mechanism to make this system flexible and extensible.

Assembling:

Figure 4.1(a) illustrates these patches stacked in two layers in the hollow space of the platform; temperature and microphone sensors directly contact the skin to collect high-quality signals. To create accessible patches for the users, each patch was punched with a representative icon on both sides of the covering material. Figure 4.2 illustrates the BioScope application process: (1) A healthcare worker selects the appropriate patches (or dummy patches) by using the embossed icon as a reference, stacks the patches on (or filling in empty spaces that are originally occupied by unused patches on) the platform, (2) inserts a battery and closes the protection cap, (3) affixes the bandage to chest, and (4) covers the entire bandage with transparent film dressings if water-proof is needed.

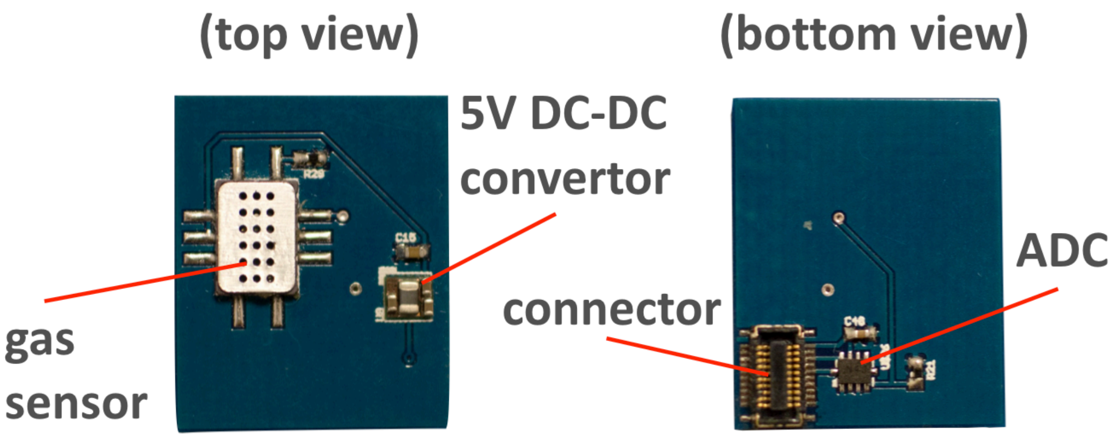


Figure 4.3: An example of using BioScope to prototype a breathalyzer.

Power source:

Each component in the system has different power supply range. Since a component may require a supply voltage higher or lower than the voltage from li-ion battery (4.2V), the voltage of power source should be converted to proper voltage. A linear regulator can be used for the component, the working voltage of which is lower than the power source in the system. If the supply voltage of a component is higher than power source, a DC-DC converter can converts the voltage to a higher voltage. In figure 4.3, the supply voltage of the gas sensor is 5V which is higher than the voltage of the battery. Therefore, we place a compact DC-DC convertor, a Texas Instruments TPS81256, to boost the voltage to 5V and provide sufficient current to enable the sensor.

Data communication:

For a sensor that communicate to the microcontroller through digital bus, I2C and SPI are two most common protocols. Those protocols is bus topology that allows microcontroller can access multiple slave components with only few pins. However, some sensors are designed to output analog signals to deliver sensory data rather than digital signals. In Figrue 4.3, a Texas Instruments ADS1114 analog-to-digital converter translates the analog signals from gas sensor to digital signals in I2C.

4.1.3 Sensor Patches

To collect biosignals, such as electrocardiogram (ECG) signals, two pre-allocated electrodes (i.e., two conductive copper areas situated 6.4 cm apart at opposite ends of the bandage) are coated with a thin layer of electrical gel (Figure 4.1(b)). The sensor patches, consisting of small sensor boards sandwiched between two thin layers of 3D-printed elastic filaments, are mounted on the bandage-like platform using connectors. To demonstrate the concept of this system, we designed six types of patch —biopotential, thermal, acoustic, mobility, interaction and recharging patches —to facilitate the collection in the most commonly monitored data in healthcare applications. The detail of those six types of patch are described in follows.

Biopotential patch:

This 23 mm × 24 mm patch, stacked in the inner layer, amplifies and filters ECG signals to enable continual cardiovascular monitoring. Cardiac activity, which can be characterized by ECG signals, is a crucial biosignal for assessing the cardiac functions of people. By amplifying the electrical potential difference measured between the two electrodes by using a Texas Instruments ADS1115 analog-to-digital converter on the patch, ECG signals can be monitored by allowing the passing of low-frequency signals from 0 to 100 Hz [1] by using a low-pass filter. A pulse can be identified by detecting spikes in the signal, thus enabling users to assess heart and respiratory rates.

Acoustic patch:

This 24 mm × 24 mm patch, stacked in the contact layer, records acoustic signals emitted by a person's body or while the person is phonating. By identifying the unique sound patterns that the body's organs generate, users can assess person's conditions. Furthermore, person's phonation can indicate social interaction, according to which users can assess whether a person is depressed or impaired cognitively. To clearly record the internal sounds of the body, a mediating instrument (e.g., a stethoscope) is required. Inspired by the design of electronic stethoscopes, we designed and attached a small sound-collecting structure (Figure 4.1(b)) on the patch that effectively amplified acoustic signals from the body and occluded environmental noise. Above the sound-collecting structure, an opening is aligned with the receiving hole of an InvenSense INMP441 microphone on the main board to guide sound waves towards the hole. In this study, we detected a person phonation, which reflected social activity, by analyzing the frequency components of the collected sound.

Thermal patch:

This 10 mm × 24 mm patch is stacked in the contact layer and measures the skin temperature, which can indicate a person's health. users can evaluate a person by identifying abnormal or varying temperatures [6]. A Maxim MAX31850 K-type thermocouple-to-digital converter detects body temperature through a thermocouple wire that protrudes from the covering elastic material to contact the skin of the person (Figure 4.1(b)).

Mobility patch:

This 11 mm × 24 mm patch, stacked in the inner layer, monitors the mobility level of a person. For example, to prevent complications caused by reduced mobility levels and assess functional recovery, users must track the mobility level of patients. On this patch, a Bosch BMA250 accelerometer is used to collect acceleration readings, which indicate whether a person is moving or stationary. The mobility level can be derived by calculating the percentage of time a person is moving.

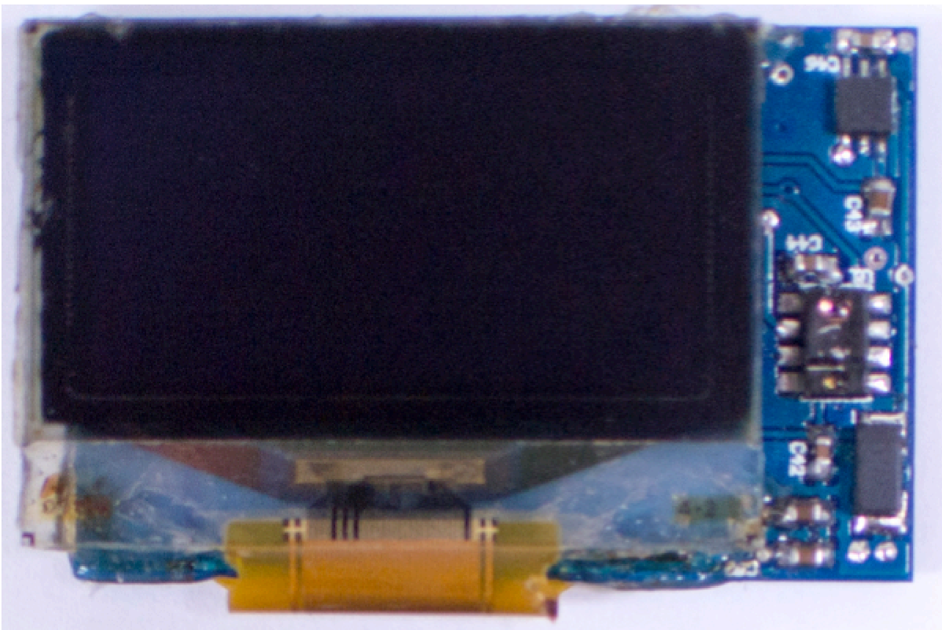


Figure 4.4: Interaction patch.

Interaction patch:

To enrich data feedback and user interaction for exercise applications, we also expanded an interaction patch that consists of a wearable display (0.96″ OLED display4), and a touchless gesture sensor (Avago APDS-9960) that is used to recognize four directions (up, down, left and right) of in-air swipe gesture. The gesture can be used to switch between different sensor's data or different data representations as shown in Figure 4.4. The interaction patch is connected to main board through stacking mechanism as well. When a mobile device attempts to establish connection with particular one of multiple wearable devices. To simplify Bluetooth pairing procedure for quickly retrieving data or configuring device, a NXP NTAG203 NFC tag is embedded in wearable device.

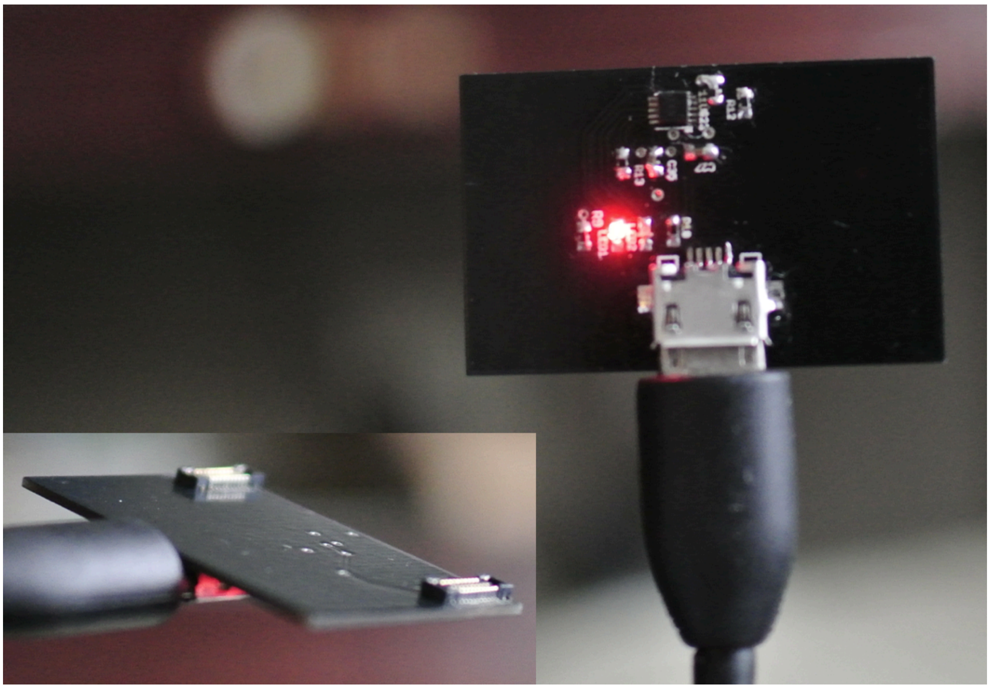


Figure 4.5: Recharging patch.

Recharging patch:

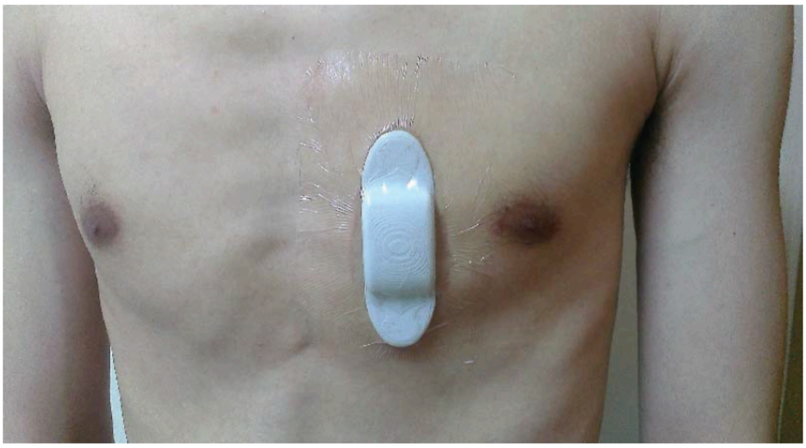
The entire is powered by a Li-ion battery with 130-mAh capacity. This patch has a USB connector to connect a 5V power source for charging and a Texas Instruments BQ24040 to regulate the charging process (Figure 4.5).

4.1.4 Explorative Experiment

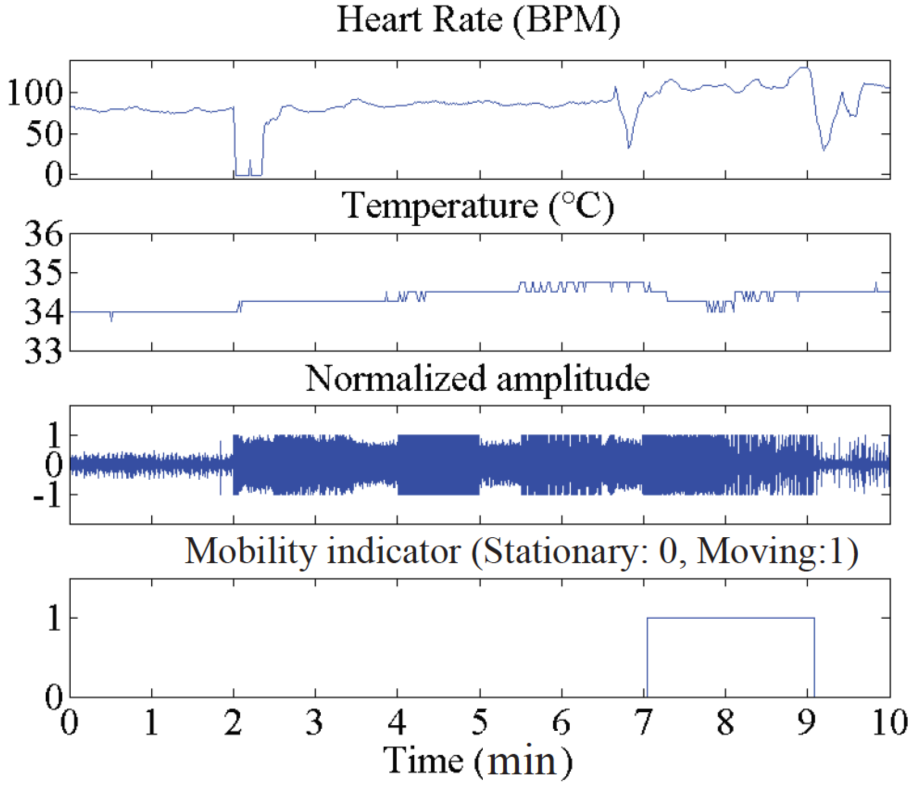
To validate system functionality, we scripted a sequence of activities to simulate conditions arising when a patient with basic functional mobility is hospitalized. Two volunteers performed the specific activities while wearing bandages equipped with all four patches on their chests, enabling us to collect data (Figure 4.6(a)). The simulations were conducted for 10 and 30 minutes in the cases of the first and second participants (P1 and P2), respectively. Activities comprised (1) lying down on a bed, (2) having a phone conversation, (3) watching TV, (4) having a face-to-face conversation, and (5) performing walking. In the experiments, the data captured were heart rate, skin temperature, received acoustic signals, and mobility indicators.

Figure 4.6(b) shows the results obtained by analyzing the data collected from P1. The readings obtained from the mobility patch indicated that P1 moved between the seventh and ninth minutes; this was an accurate assessment of the patient's behavior during that time. While walking, P1's heart rate increased relative to that while stationary between the start and the seventh minute. When the posture of the patient drastically changed, such as when P1 stood up near the second, seventh, and ninth minutes, the ECG signals were distorted [4], producing a dip in the calculated heart rate. The sounds generated by clothes rubbing against the bandage when P1 moved adversely affected the quality of detected internal sounds, causing the amplitudes to increase between the seventh and ninth minutes. After filtering out sounds generated by movement, however, we could still detect when P1 phonated between the second and seventh minute. Based on the vocal resonance of the body [5], we detected phonation by identifying the frequency components of sounds higher than the 0- to 3-kHz frequency range of the human voice [7]. Finally, the body temperature varied minimally (34°C $\sim$ 35°C) and was near the normal skin temperature of the human chest [6]. Overall, the results accurately reflected the activities performed by the participants.

To examine whether the system can detect reasonable values for the average heart rate, total moving duration, average skin temperature, and total phonating time, we analyzed the data collected from P2 over 30 minutes. The total moving duration was determined to be 7.2 minutes (actual value: 6.9 minutes), with an error of 4.0%. The average heart rate was 81.5 and 100.3 beats respectively. Because P2 did not perform intensive exercise, the average temperature did not vary significantly, remaining near 33.9◦C. By identifying the high-frequency components embedded in the high-pitched sounds collected when P2 was stationary, P2 was deter- mined to have phonated for 635.5 seconds (actual value: 564.0 seconds), with an error of 12.7%. per min (BPM) when P2 was stationary and moving, respectively. Because P2 did not perform intensive exercise, the average temperature did not vary significantly, remaining near 33.9◦C. By identifying the high-frequency components embedded in the high-pitched sounds collected when P2 was stationary, P2 was deter- mined to have phonated for 635.5 seconds (actual value: 564.0 seconds), with an error of 12.7%.



(a) Stacked bandage affixed to patient's chest



(b) Results from data collected by BioScope

Figure 4.6: Four steps for applying bandages.

4.2 ...

4.3 ...

Chapter 5

Conclusion

Bibliography

[1] B. Al-Shaikh and S. Stacey. *Essentials of Anaesthetic Equipment*. Churchill Livingstone, 1995.

[2] A. A. Ali, S. M. Hossain, K. Hovsepian, M. M. Rahman, K. Plarre, and S. Kumar. mpuff: Automated detection of cigarette smoking puffs from respiration measurements. In *Proceedings of the 11th International Conference on Information Processing in Sensor Networks*, IPSN '12, pages 269–280, New York, NY, USA, 2012. ACM.

[3] D. Camarillo, J. Mattson, M. Flynn, S. Yang, P. Shull, R. Shultz, G. Matheson, and D. Garza. Head contacts in collegiate football measured with an instrumented mouthguard. *British Journal of Sports Medicine*, 47(5):e1–e1, 2013.

[4] A. Chan, N. Ferdosi, and R. Narasimhan. Ambulatory Respiratory Rate Detection using ECG and a Triaxial Accelerometer. In *Proc. IEEE EMBS 2013*, pages 4058–4061, July 2013.

[5] J. Dacre and P. Kopelman. *A Handbook of Clinical Skills*. Manson, 2002.

[6] R. A. Freitas. *Nanomedicine, Vol. I: Basic Capabilities*. Landes Bioscience, 1999.

[7] Gartner. Forecast: Wearable electronic devices, worldwide. 2016.

[8] J. Greenbaum and M. Kyng, editors. *Design at Work: Cooperative Design of Computer Systems*. L. Erlbaum Associates Inc., Hillsdale, NJ, USA, 1992.

[9] N. D. Lane, P. Georgiev, C. Mascolo, and Y. Gao. Zoe: A cloud-less dialog-enabled continuous sensing wearable exploiting heterogeneous computation. In *Proceedings*

of the 13th Annual International Conference on Mobile Systems, Applications, and Services, MobiSys '15, pages 273–286, New York, NY, USA, 2015. ACM.

[10] E. C. Larson, T. Lee, S. Liu, M. Rosenfeld, and S. N. Patel. Accurate and privacy preserving cough sensing using a low-cost microphone. In *Proceedings of the 13th International Conference on Ubiquitous Computing*, UbiComp '11, pages 375–384, New York, NY, USA, 2011. ACM.

[11] C.-Y. Li, Y.-C. Chen, W.-J. Chen, P. Huang, and H.-h. Chu. Sensor-embedded teeth for oral activity recognition. In *Proceedings of the 2013 International Symposium on Wearable Computers*, ISWC '13, pages 41–44, New York, NY, USA, 2013. ACM.

[12] K. Lorincz, B.-r. Chen, G. W. Challen, A. R. Chowdhury, S. Patel, P. Bonato, and M. Welsh. Mercury: A wearable sensor network platform for high-fidelity motion analysis. In *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems*, SenSys '09, pages 183–196, New York, NY, USA, 2009. ACM.

[13] F. Mokaya, R. Lucas, H. Y. Noh, and P. Zhang. Myovibe: Vibration based wearable muscle activation detection in high mobility exercises. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, UbiComp '15, pages 27–38, New York, NY, USA, 2015. ACM.

[14] F. O. Mokaya, B. Nguyen, C. Kuo, Q. Jacobson, A. Rowe, and P. Zhang. Mars: A muscle activity recognition system enabling self-configuring musculoskeletal sensor networks. In *Proceedings of the 12th International Conference on Information Processing in Sensor Networks*, IPSN '13, pages 191–202, New York, NY, USA, 2013. ACM.

[15] M. J. Muller. PICTIVE-an exploration in participatory design. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '91, pages 225–231, New York, NY, USA, 1991. ACM.

[16] M. J. Muller. The human-computer interaction handbook. chapter Participatory Design: The Third Space in HCI, pages 1051–1068. L. Erlbaum Associates Inc., Hillsdale, NJ, USA, 2003.

[17] J. Nielsen. Iterative user-interface design. *Computer*, 26(11):32–41, Nov. 1993.

[18] M. A. Schilling. Toward a general modular systems theory and its application to interfirm product modularity. *Academy of management review*, 25(2):312–334, 2000.

[19] R. Thompson, I. Kyriazakis, A. Holden, P. Olivier, and T. Plötz. Dancing with horses: Automated quality feedback for dressage riders. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, UbiComp '15, pages 325–336, New York, NY, USA, 2015. ACM.

[20] S. D. Tripp and B. Bichelmeyer. Rapid prototyping: An alternative instructional design strategy. *Educational Technology Research and Development*, 38(1):31–44, 1990.

[21] K. Ulrich. The role of product architecture in the manufacturing firm. *Research policy*, 24(3):419–440, 1995.

[22] D. Van Duyne, J. Landay, and J. Hong. *The Design of Sites: Patterns for Creating Winning Web Sites*. Prentice Hall, 2007.

[23] M. Walker, L. Takayama, and J. A. Landay. High-fidelity or low-fidelity, paper or computer? choosing attributes when testing web prototypes. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 46, pages 661–665. SAGE Publications, 2002.

[24] K. Yatani and K. N. Truong. Bodyscope: A wearable acoustic sensor for activity recognition. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, UbiComp '12, pages 341–350, New York, NY, USA, 2012. ACM.

[25] C.-W. You, Y.-F. Lin, C.-Y. Li, Y.-L. Tsai, M.-C. Huang, C.-H. Lee, H.-C. Wang, and H.-H. Chu. Kediary: Using mobile phones to assist patients in recovering from

drug addiction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI ’16, pages 5704–5709, New York, NY, USA, 2016. ACM.