Itchtector: A Wearable-based Mobile System for Managing Itching Conditions

Jongin Lee[1], Daeki Cho[2], Junhong Kim[1], Eunji Im[1], JinYeong Bak[1], Kyung Ho Lee[3], Kwan Hong Lee[4], John Kim[1]
[1]School of Computing, KAIST, [2]NEC Laboratories America,
[3]Department of Dermatology, The Catholic University of Korea, [4]AcademicMerit
{jongin.lee, jh15, imej, jy.bak, jjk12}@kaist.ac.kr
[2]dkcho@nec-labs.com, [3]beauty4u@catholic.ac.kr, [4]kwan@academicmerit.com

ABSTRACT
Severe itching conditions such as eczema or atopic dermatitis can have a significant impact on one's quality of life. Unfortunately, many of these conditions cannot be cured, and the focus is often on properly controlling or managing the condition. Thus, it is important to understand or objectively monitor how one's scratching behavior changes, based on medication or treatment or environmental conditions. In this work, we explore how wearable devices can support people with itching conditions to better manage their conditions. We carried out a three-phase study with 40 participants and 2 dermatologists to understand the implications of various system features and designs. Based on interviews with patients and doctors, we incorporated medical guidelines for treatment and patients' needs in the proposed Itchtector – a smartwatch-based mobile system to monitor itching behaviors and provide objective information about the user's scratching behaviors. Using the Itchtector prototype, we evaluated performance and possible acceptance with subjects.

ACM Classification Keywords
J.3 Life and Medical Sciences: Health; H.5.3 Group and Organization Interfaces: Computer-supported cooperative work

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Itching management; mobile system; nocturnal scratching

INTRODUCTION
Patients with chronic itching diseases such as atopic dermatitis and eczema need to manage their itching symptoms since the severe itching can affect their quality of life. In particular, atopic dermatitis (AD) is common among children, and its prevalence has increased, especially in developed countries [22]. Parents of the afflicted child can suffer from parental anxiety and psychological distress when managing the child's symptoms [41]. Adult patients with AD also have difficulty managing their symptoms because of environmental conditions (e.g., temperature, humidity, etc.) as well as genetic factors, all of which need to be considered when managing their itching conditions [1]. When the condition worsens, patients often visit a doctor or a dermatologist; however, since the causes of atopic dermatitis can vary significantly, even doctors can have a difficult time identifying which factors are affecting the patient's itching condition, and as a result, trial-and-error approach to treatment is commonly used [3].

Consequently, patients with severe itching conditions are often left to manage their own itching symptoms by themselves, avoiding exacerbating factors when possible. For this purpose, keeping a diary [24] is encouraged as a method to help manage symptoms – including keeping track of the foods they eat, any medication or treatment that they receive, any exacerbating factors, etc. The purpose of the diary is to help identify factors that affect their symptoms so that they can be avoided. However, maintaining a daily diary can be very difficult and in particular, representing one's condition (e.g., how severe is your current condition? has the condition improved?, etc.) can be very subjective and difficult to quantify [44]. To help patients manage their conditions more effectively, the Patient-Oriented SCORAD (PO-SCORAD) index [37] was introduced to better understand the itching severity of patients. However, this index also relies on subjective input from the patients, which can be affected by their mental state. In this work, we explore opportunities to support patients with itching conditions to better manage and control their conditions, using wearable mobile systems and services.

In this paper, we propose a new opportunity for wearable computing to help better manage itching conditions The proposed system can provide a number of benefits, including better communication with doctors, help in establishing an objective understanding of a patient's itching condition, and automatic tracking of external environmental factors that might affect their itching conditions. By conducting extensive interviews with subjects who have itching conditions as well as dermatologists, we identified how the lack of an objective metric or system to track subjects' condition can cause frustration and difficulty in managing their itching conditions. These difficulties extend to when subjects communicate with their doctors during medical visits, since they had a hard time expressing how their conditions have changed (e.g., has my condition improved since taking the new medication?). Based on the preliminary study, we propose *Itchtector* – a mobile system that measures the scratching behavior of users, using sensor data from smartwatches. The system quantifies and measures a number of scratch events to provide accurate feedback about

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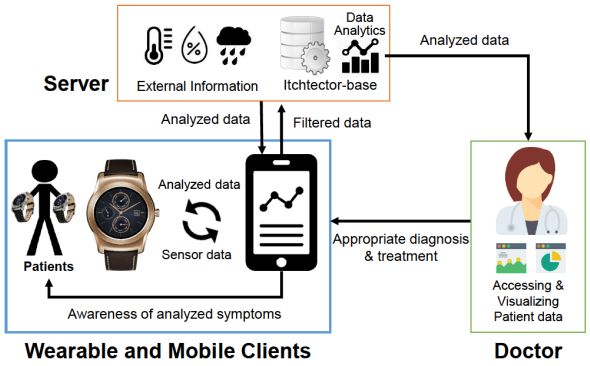


Figure 1. A high-level overview of a system that we proposed for maintaining itching conditions.

their itching condition. We first carefully designed a basic service flow and the key functionalities of the Itchtector using various mockup applications, and then explored subject's acceptance and the implications of the service and system. The final component of the study included development of an initial Itchtector prototype and an evaluation of its performance for tracking nocturnal scratching in a separate user study.

Figure 1 provides an overview of the possible scenarios that we envision for the Itchtector. The system consists of a mobile client and a server. The mobile client aggregates sensor data from the smartwatch and uploads the data to a server after preprocessing (e.g., noise filtering). When the server receives the data, it analyzes the data and stores the results in the database called Itchtector-base. When the results are available on the server, a doctor can access and interpret the results using the system to provide appropriate diagnosis and treatment. The Itchtector prototype in this study does not fully implement all of the components of this vision yet. However, this paper is a first step towards such a system, which can be beneficial to both doctors and patients. We also discuss how the Itchtector system can be extended in a field study, to communicate more accurate information about the patient's conditions to their doctors, possible user experience to control their chronic disease, as well as system challenges in the implementation.

RELATED WORK

Nocturnal Scratches in Medical Applications

Although the most accurate method for recording scratching behavior is to use an infrared video and manual labeling, it is very time consuming to manually inspect several hours of recordings. In addition, attempting to record scratching when the hands are poorly positioned or hidden (e.g., the hands are covered with a blanket) makes it even more difficult to identify scratching behaviors [17]. Actigraphy [14] and Actiwatch [15] devices (watch-type bands with an accelerometer sensor) have previously been used to measure nocturnal scratching in medical applications. Benjamin et al. [8] showed that the mean value of accelerometers is positively correlated to scratching behaviors, compared to data from an infrared camera. Other prior works [21, 7] have also shown that objective clinical scores, including SCORAD, TST%, and SASSAD, are correlated with wrist activities. However, these prior works still have limited accuracy, since they have a tendency to identify other body movements (e.g., turning over while sleeping, etc.) as scratches. Accelerometer threshold values are commonly used to determine scratching events, however, some non-scratch movements are still identified as scratches, and result in false-positive detection. A recent work [45] showed the limitations of using just the threshold values to detect scratching behaviors, and demonstrated that other body movements can cause noise in the data.

Sensor Analysis Algorithms for Scratch Detection

Recently, alternative approaches for detecting nocturnal scratching using machine learning algorithms have been suggested [18, 32, 39]. A number of activities (i.e., walking, scratching and restless movements) can be differently clustered using K-means [18], and among these activities, logistic regression has also been used for scratch detection [32]. However, these works use the averaging of the X, Y, and Z acceleration vectors, which weakens the periodic pattern of a scratching signal. Moreover, these studies did not consider scratching signals during real sleep (i.e., they only simulated the scratching data for scratch model validation). Although HealthSense [39] uses 3 vectors of acceleration for scratch detection with three different machine-learning techniques (Naive Bayes, C4.5, and a neural network method), they do not consider wrist orientation during scratching. Our work differs from the above works in that the Itchtector system not only uses orientation-invariant analysis to maintain the periodicity of scratching movements, but also builds scratching models that are consistent with the unconscious scratching that occurs in real sleep.

Mobile based Healthcare Systems

While a significant amount of research has been conducted on combining mobile systems and healthcare, to the best of our knowledge, very few studies have actually looked at leveraging mobile systems to monitor the behavior of patients that experience itching problems. Although dermatological systems such as skin cancer detection [34] and monitoring newborn jaundice [12] have been suggested, they did not focus on itching or scratching. HealthSense [39] described the possibility of using sensors to detect scratch motions but they did not implement a full system and did not apply the system to patients with itching conditions.

Most of the healthcare mobile systems are proposed to improve the self-management ability of patients or caregivers [33, 11] or the communication process between patients and clinicians [20, 35, 30]. Recently, Kim et al. [23] and Chung et al. [11] have studied the feasibility of applying patient's data (e.g., food intakes, symptom logs) into the clinical context. Our proposed system makes improvements of both the self-management ability and the communication between patient and clinician by automatically quantifying the scratching behavior based on the machine learning technology.

Mobile wellness diaries or loggers are used as a self-monitoring system to manage chronic symptoms such as diabetes [4], chronic heart failure [16], and sleep disorders [27]. The early stage of those systems has required the user to manually input the data. However, recent systems automate these manual processes using the various sensors in the mobile [29, 27] that can potentially make the data collection more reliable and objective. Similar to these, our system also takes minimal input from the user and automates the data collection and the scratch behavior analysis.

STUDY PROCEDURE AND METHOD

Study Procedure Overview

Figure 2 illustrates our overall study procedures and methods, which consisted of three phases. Phase 1 was used to investigate the high-level motivation of subjects, as well as to obtain medical guidelines or approaches for itching diseases from dermatologists for our service design. Based on these motivations and guidelines, we designed the Itchtector service to help doctors and people who have chronic itching conditions to better manage their itching conditions. To study the implications of the Itchtector, a two-step user study was conducted in Phase 2. In the first step, a mockup-driven user study was conducted using mockup smartphone and smartwatch interfaces to provide a realistic user experience and obtain feedback from both the subjects and doctors. A scenario-driven user study was also performed within Phase 2 to obtain feedback on the different service usage scenarios. As a final part of our study, we implemented a system prototype of our system and evaluated its performance.

Participants: Table 1 summarizes the participants for the three phases of this study. Proper IRB permission was obtained for all phases of this study. We recruited participants with chronic itching, and also included the parents of a child with atopic dermatitis (AD). For Phase 1, we recruited the parents of 2 female children (9 years and 5 years) with AD and 12 other participants (mean = 26 years, sd = 10, 6 male and 6 female). Their skin diseases varied but the prevalent disease was AD. For Phase 2, to avoid potential bias from Phase 1, we separately recruited the parents of 1 female child (2 years) with AD and 10 other participants (mean = 24 years, sd = 9, 7 females, 3 males). 15 subjects (mean = 23 years, sd = 4, 8 males, 7 females) were also recruited in Phase 3. We also conducted a pre-survey to understand patients' current conditions, including demographics and the Patient-Oriented SCORAD (PO-SCORAD) index [37], a self-assessment tool that represents the severity and extent of itching conditions.

Phase 1 was conducted to understand current medical approaches being used to treat or alleviate itching conditions, and the subjects' own difficulties when managing their itching conditions. We first consulted two dermatologists separately in one time face-to-face meetings of one hour. Based on these consultations, we established guidelines to be used in our service, so that the doctors who use the proposed system can provide a better diagnosis.

In parallel with the expert study with dermatologists, we conducted a semi-structured interview with the 12 participants and 2 parents of the child with AD, via a one hour face-to-face meeting. We asked them about the approaches they used to manage their itching conditions, and their difficulties they encountered. To analyze the qualitative data from the interview transcripts, two researchers segmented the direct quotes which represented a single idea, and iteratively clustered the segmented quotes into high-level categories, until arriving at broad themes.

Phase 2 consisted of designing the Itchtector service and mockup, including a mockup-driven user study and a scenario-driven user study. Based on the findings in Phase 1, we designed Itchtector – a wearable system in which sensor data

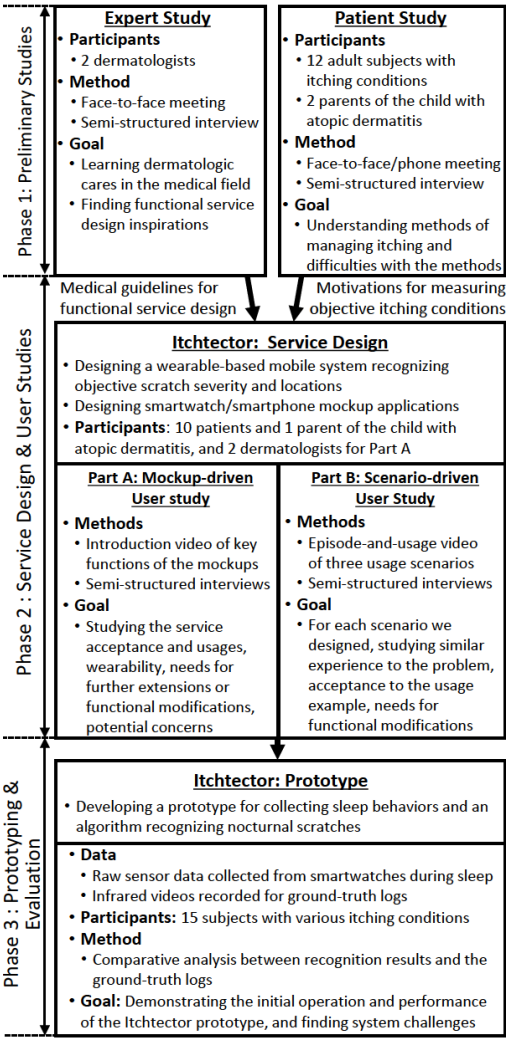


Figure 2. Overall study procedure for Itchtector system.

is collected by smartwatches and then analyzed to recognize scratching counts/location. The analyzed data can be used by patients to better manage their itching conditions and can also be provided to their doctors for improved treatment. External sensor data was also collected and combined with the scratch data to provide a better understanding of the influence of external factors on the severity of itching.

To investigate the potential usages of Itchtector with doctors and subjects, we conducted a two-part user study through individual face-to-face interviews. In the first part, we showed videos of mockup Itchtector functions to explore potential usages of our designed system, as well as service acceptance, the usability of the wearable device, possible extensions or functional modifications, and potential concerns. Another part of Phase 2 was a scenario-driven user study that consisted of three different application scenarios identified in Phase 1. User scenario videos were created which used the mockup interface to demonstrate how Itchtector could be used in different patient scenarios, and feedback was obtained for each scenario. Since the scenarios were based on subjects' experiences, we did not interview doctors for this part of the study. The first part of Phase 2 was done separately from the second part in order to obtain feedback from the participants

P#	Gender	Age	Diagonosis	Period (years) of disease
P1	F	25	AD	20
P2	F	30	SD	5
P3	M	29	PS, SD	4
P4	F	31	AD	26
P5	F	25	AD, Urticaria	18
P6	M	21	AD	16
P7	F	30	Urticaria	2
P8	M	26	AD	26
P9	M	25	AD	12
P10	M	24	AD	18
P11	M	40	AD, Heat rash	29
P12	F	43	AD	43
P13	F	9 (child)	AD	9
P14	F	5 (child)	AD	5

(a) List of participants in Phase 1

P#	Gender	Age	Diagonosis	Period (years) of disease
P15	F	30	AD	25
P16	F	22	Urticaria	12
P17	F	21	AD, CD	26
P18	M	30	AD	21
P19	F	27	NE, AD	26
P20	M	37	AD	12
P21	F	25	Eczema	1
P22	M	29	AD, SD, Eczema	24
P23	F	20	AD	15
P24	F	26	AD, DU, Eczema	24
P25	F	2 (child)	AD	2

(b) List of participants in Phase 2

P#	Gender	Age	Diagnosis
P26	F	20	AD, Allergy
P27	F	26	AD
P28	F	22	Urticaria
P29	M	35	Urticaria, Allergy
P30	M	21	Shingles, Eczema
P31	M	21	AD
P32	M	21	AD, Eczema
P33	F	26	AD, PS, Angioma
P34	M	27	AD
P35	M	27	AD
P36	F	19	AD, Heat rash
P37	M	21	SD
P38	F	20	AD
P39	M	24	AD
P40	M	20	AD, Eczema

(c) List of participants in Phase 3.

AD: Atopic dermatitis, CD: Contact dermatitis, DU: Dermatographic urticaria, NE: nummular eczema, SD: Seborrheic dermatitis, PS: Psoriasis

Table 1. Lists of participants for the three phases of this study.

regarding the system and interface, without biasing them with the scenarios that we had developed.

Phase 3 focused on developing an algorithm to recognize nocturnal scratching using an Itchtector prototype and evaluating the initial performance. We focused on nocturnal scratching, since participants are not necessarily aware of their scratching behaviors while sleeping. The Itchtector prototype was implemented to collect various scratching and non-scratching behaviors during the entire sleeping period, from subjects who had various itching conditions. Then, an Itchtector algorithm was designed to reflect the periodic patterns of nocturnal scratching.

PHASE 1: PRELIMINARY STUDIES

Medical Approaches to Itching Diseases

We interviewed two dermatologists to learn and understand the methods for diagnosing skin diseases that cause severe itching (e.g., atopic dermatitis), and medical approaches used to measure itching conditions.

The dermatologists stated that the process of diagnosing skin diseases that cause severe itching, such as atopic dermatitis, is mainly based on examining skin lesion, as well as patients' comments and any historical diseases the patient might have had. With visible skin lesions, doctors can better evaluate skin conditions and determine a diagnosis for treatments since the diagnosis of skin disease is fundamentally based on the physical distribution, character, and shape of the skin lesions [19]. Accordingly, when there is no skin lesion, it makes diagnosis more difficult, and the doctors often try to find other aspects that can possibly affect the itching, such as internal secretions, psychiatry, nervous systems, environmental factors, etc. Patients' comments about the symptoms they experience are also considered part of the diagnosis, but these comments are not completely reliable, since the diagnosis needs to be primarily based on objective information [38].

Dermatologists also noted that the medical indexes [1](e.g., SCORAD, EASI, etc.) that are commonly used are not practical in many clinical settings since the methods require significantly more consultation hours, and can create privacy issues, since the skin condition of the patient's entire body needs to be examined. Instead, the examination is often limited to the skin lesions that the patients present.

[1]SCORAD (SCORing Atopic Dermatitis) and EASI (Eczema Area and Severity Index) are survey-based medical tools used to measure the extent and severity of atopic dermatitis or eczema, including the location of where the skin conditions occur.

Patients' Experiences in Managing Itching

We interviewed 12 participants with itching conditions and 2 parents of the child with AD. Table 1(a) summarizes the participants. We first asked each a broad question regarding how they managed their itching condition. Most of the participants commonly used medicines (e.g., topical steroids) when their itching symptoms became worse. They commonly used moisturizers (e.g., lotions) to manage their itching conditions. While foods and environmental factors (especially temperature and humidity) could impact their itching condition, most of the participants felt that it was difficult to control such factors. Most of the participants felt that maintaining a healthy lifestyle (e.g., getting enough sleep, avoiding fast food, minimizing stress, etc.) was important to minimize their itching condition. Because of the difficulties in managing their conditions, some participants (P4, P7, P12) also spent significant effort to research itching symptoms on their own, through the Internet and books, while trying to share information with others that have similar conditions. We categorized the difficulties as well as their hardships in managing their itching symptoms, using the six categories below.

Difficulties in communicating with doctors

1. Explaining scratching severity and locations of itching: Some subjects pointed out how difficult it was to explain their itching symptoms when they visited the doctor, and in particular, when the appearance of their skin lesions did not reflect the itching severity. (P7) *"My skin lesions are severe every night. (...) however, I could not show the doctor the skin lesions in the evening. I felt like I was a liar in front of the doctor. (...) Doctors did not seem to understand my symptoms."* The parent of the child with AD (P14) also complained about the diagnosis from the doctor: *"I thought that my child's itching symptoms were severe. But whenever we consulted with the doctor, my child's symptoms seemed to get better at the time of our doctor's visit and the doctor did not understand my child's severe symptoms."*

Difficulties in managing their own itching conditions

2. Late recognition of worsening itching severity and sites: We also found that some subjects were slow to recognize the growing severity of their itching: (P5) *"I was not aware of my severe itching condition since the condition worsened very*

slowly. I only recognized the severity of my condition when I noticed the large skin lesion with a wound." (P6) *"My symptom sometimes got worse gradually. (...) It was very difficult to recognize that my symptoms were getting worse. I became aware of my severe symptom after the symptom had become totally severe and needed medical cares from doctors."*

3. Understanding external factors affecting itching: All subjects were aware that external factors (e.g., temperature, season, locations, etc.) can affect their itching conditions. Some participants (P4, P5, P10) became familiar with which particular factors affected them only because they have had the itching condition for a very long period of time (e.g., 15 years). However, many participants did not know exactly which factors had a serious impact on their itching conditions: (P1) *"My itching symptoms were sometimes severe, but I did not know the reason. (...) I thought the temperature or humidity were not strongly related to my symptoms, but I am not sure about that either."* In particular, P2 stated difficulties in identifying geographical location effect. *"I recently determined that my itching symptom got worse whenever I visited a room with old books. The air quality in the rooms might affect my itching symptoms."* Some patients mentioned seasonal or long-term effect: (P8) *"My symptom seemed to get severe during the winter. I also thought that humidity might affect my itching symptom"* (P9) *"I felt my itching seemed to be severe every other year, but doctors did not agree with my opinion."*

4. Careful use of steroids or antihistaminic medicines: All subjects including the parents expressed concerns about the side effects of the medicines that they used. The concern was most severe for the child's parents: (P13, child) *"When I used steroid ointment on my child, the itching condition definitely improved. However, I have heard that too many steroids can lead to early puberty. (...) Because my child is young and a female, I make a big effort to avoid using steroid ointments when possible."* Most of the adult participants stated that steroid ointment was only used when their symptoms became very severe: (P4) *"I try to avoid using steroid ointment more than once a day since I know the side effects of the ointment. Instead, I tried to treat my itching sites with Vaseline or saline solutions."*

Psychological and social difficulties

5. The anxiety produced by forthcoming severe itching: We found that some of the participants who suffered from severe itching had anxieties about severe scratching that would occur during sleep: (P7) *"I had some anxiety around sleeping due to the severe itching and that led to insomnia. (...) If I have a meeting in the morning, I am very anxious about my poor sleep quality and dozing off during the meeting. As a result, I had to have sleep medication before going to sleep."* In spite of the anxiety, some subjects pointed out they worried about whether to use the medicine or not, due to the risk of overdose. (P5) *"Because of my severe itching experiences, I used a steroid ointment whenever I felt my itching was getting worse. (...) I always worried whether my use of steroids could cause an overdose."*

6. Difficulties maintaining a normal social life: Nearly all of the participants expressed frustrations about how the itching affected their social lives. (P4) *"Since I felt sleeping helped to alleviate my itching, I always went to sleep whenever I felt my itching was severe. (...) So, I did not do my homework sometimes and finally gave up the class for my health."* (P5) *"If my severe itching starts, I even do not think any social activities. (...) I could not wear tight-fitting clothes but always wore clothes with cotton. (...) I was not able to take a shower with hot water for a long time. I felt frustrated because I could not enjoy a normal social life."*

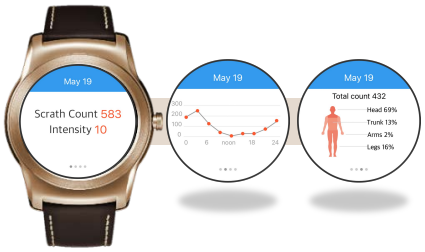


Figure 3. Smartwatch mockup interface.

PHASE 2: SERVICE DESIGN OF ITCHTECTOR

Based on the findings in Phase 1, we defined three high-level opportunities for the wearable devices.

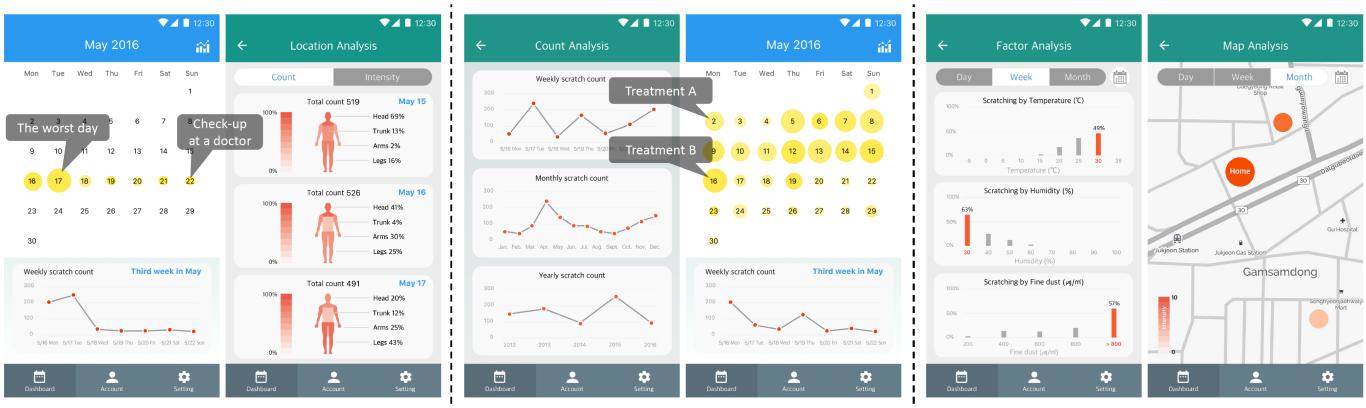
The first opportunity was to improve the communication between the doctors and the patients in conveying the patient's itching conditions. Since the communication between doctors and patients primarily occurs in a clinical setting, doctors often do not completely understand their patient's itching condition. Thus, properly recognizing scratching behaviors (and how that behavior changes) will be helpful for both doctors and patients.

The second opportunity was to provide an objective feedback to the subject on their itching conditions, to allow them to better manage their itching symptoms. In particular, an accurate awareness of the current itching condition can help the subject avoid the overuse of medications.

The third identified opportunity was to connect the scratching behaviors with various exacerbating factors, so that information could be used to help determine which factors were negatively affecting the subjects. Patients often rely on their own subjective experiences to understand the exacerbating factors. However, knowing which factors were actually associated with severe scratching behaviors can provide an objective consideration of how the external factors may influence itching for each individual subject.

Service Design and the Key Functions of Mockups

We implemented mockup applications for both smartwatches and a smartphone, which included three key functions that satisfied the three opportunities discovered in Phase 1. The reason for implementing the mockups was to obtain early feedback from users about our initial service concept [13], before fully implementing our system or service. Figure 3 and Figure 4 show the smartwatch and smartphone mockup interface, respectively. The key functions of the mockups are to display 1) trends in scratching count/locations according to the time/month/year, and 2) scratching count in relation to exacerbating factors. Scratch behaviors were defined as periodic movements lasting longer than 3 seconds [6, 18], and scratch locations were carefully divided with doctors' consultation before designing the mockup interfaces, and the external factors were also carefully selected based on the patients' experiences we obtained in Phase 1.



(a) (b) (c)

Figure 4. Smartphone mockup interfaces for the 3 different scenarios: (a) Scenario 1 interface showing information on scratch count and location, (b) Scenario 2 interface shows how scratch behavior changes over time and how it might correlate with different treatments used, and (c) Scenario 3 used to better understand objective external factors that might affect itching conditions. The information in Scenario 2 showed an example with significant long-term usage. However, long-term use of wearables is a challenge [2] and needs to be addressed for Itchtector as well.

Part A: Mockup-driven User Study

The first part of the user study was performed with mockups that we designed, and the goal of the user study was to determine service acceptance, wearability as well as to identify any potential concerns or possible extensions or modifications. The participants were shown the mockup application on both the smartwatch and the smartphone devices; in addition, a video was also shown that introduced the functionality of the applications. The mockup-driven study was conducted with both the doctors and the subjects.

Doctor's Feedback

We interviewed two dermatologists individually, with each interview lasting for approximately one hour. The questions were mainly about how the functions in the mockup could be used to improve diagnosis.

Additional information for better diagnosis: The doctors indicated that the information on scratching counts and scratching locations could be used for better diagnosis, since some skin conditions do not have any visible appearance on the skin. The "itch-scratch" cycle [46] behavior can also result in the temporary disappearance of the itching condition: *"If the doctor can observe scratch counts over time, we can determine whether the symptom has gotten worse or not. Normally, we are limited to checking secondary scratch marks on the skin lesion for the diagnosis."* Doctors also stated that an objective scratch count information could be used to understand the effect of medication, since the medications can often take up to two weeks to have an effect on the skin [9].

Better communication with patients: Both doctors also stated that knowing how the scratching behaviors change can help them communicate with their patients: *"I sometimes argue with my patients when I insist the wounded skin lesions are from scratching* (i.e., factitial dermatitis [36]) *while the patient might insist they did not scratch that particular location. If an objective record of scratch count and location are available, this type of miscommunication can be resolved."*

Patient's Feedback

We also individually interviewed 10 subjects and 1 parent of the child with AD. Each interview lasted for approximately 30 minutes, and the results are summarized in Table 2. To provide details from their feedback, we include some representative quotes below.

P#	Service acceptance	Wearability problem	Privacy problem
P15	N	Y	N
P16	Y	N(c)	Y
P17	Y	N(c)	N
P18	Y	N(c)	N
P19	Y	Y	Y
P20	Y(c)	N	N(c)
P21	N	Y	N
P22	Y	N(c)	N
P23	Y	N(c)	N
P24	Y	N(c)	N(c)
P25	Y	Y	N

Table 2. A summary of the mockup-driven user study in Phase 2. (Y: yes, N: no, (c): conditional response)

Service acceptance of Itchtector: Eight participants and one parent showed interest in using our service to manage their itching conditions: (P22) *"If I had it[Itchtector], I could be aware of my itching condition more objectively. (...) Since I am used to my itching, I think it is very difficult to recognize when it is getting worse. (...) I always become aware that my itching conditions have become severe after my symptoms have gotten too bad. "* The parent (P25) also stated: *"Since I cannot always be with my child because of my job, if I have it[Itchtector], it would help me better understand my child's itching conditions."* P16 really wanted to use our service to find factors that were affecting her itching condition. *" Since the doctors do not know the cause of my itching, I think I should avoid* any *factors that could affect my itching. As a result, it[Itchtector] would be very helpful to me. (...) How much is it?"* Interestingly, P22 and P23 pointed out that the information provided by the system could provide some reassurance: (P23) *"I currently do not have a good understanding of my itching symptoms. (...) I would be more reassured and comforted if I had some understanding of the changes in my itching condition."* P23's comment provided a new opportunity for our service design – some people have psychological difficulties because of their itching conditions, and a system like Itchtector can help provide some sense of reassurance. P17 liked having the ability to know how their scratching location changed over time: *"It would be very useful to know the scratching locations.*

In my case, I am only aware of the scratching locations when they start to bleed from excessive scratching."

P20 agreed about the usefulness of our service but expressed concerns about the technical feasibility of the system. P20 strongly agreed with our service, suggesting that the service could be used to complement his current treatment diary to find and avoid exacerbating factors that were affecting his itching condition. *"I think that [Itchtector] would be better for my current diary since it can automate the process of recording much of the information that would go into a treatment diary. (...) Is it technically feasible to recognize scratching behaviors?"*

P15 and P21 declined our service because their itching symptoms were near their wrists. P15 could not wear regular watches because of her itching condition. P21 stated that her itching symptoms were mainly located on both of her hands and that would make it difficult to use smartwatches.

Functional Extensions to the Service: Four subjects and one parent suggested extensions to our service based on their experiences. P17 and P20 wanted an 'alert' function if their itching symptom became too severe, based on collected data. P17 even wanted the device to wake her up if this happened during sleep: *"I can control my scratching during the day but cannot control the behavior while sleep. If my symptoms get worse while I am asleep, I would like the system to wake me up – perhaps through a smartwatch alarm."* P18 would have liked the service better if it could provide guidance or additional information on how to alleviate his itching condition if it got worse. *"I felt most of the information provided was simply 'data'. (...) I would have preferred if the service could perform all of the analysis and provide some treatment guidelines to me."* Interestingly, P22, who is a software developer, suggested developing a smartwatch widget that always showed up on the screen, as it would easily help him to better understand his condition – e.g., similar to a weather widget. The parent (P25) of the child with AD wanted to see whether food information of what food the child has eaten could also be displayed on the calendar, to understand the impact of food on the itching conditions.

Wearability of the smartwatch: Eight subjects (out of 11) felt that wearing smartwatches before going sleep would be acceptable and not cause any inconvenience. However, four female participants (P16, P17, P23, P24) suggested using alternative devices that were smaller and weighed less – such as Jawbone or Mi-Band. P18 and P22 also preferred to change to another lighter devices since they already had previous experiences with lightweight healthcare devices during sleep. P24 commented that wearing two smartwatches would look "weird" during the day, but she would wear two smartwatches if it helped her in managing her itching condition. P19 was skeptical about using smartwatches because she was very negative about devices collecting her biometric data. As mentioned earlier, P15 and P21 did not want to wear watches at all because of their itching symptoms on their wrist, near where the smartwatches would be worn. The parent of P25 accepted the service but pointed out that smartwatches would be too big for her child.

	Similar experience to the episode in scenarios			Acceptance to the usage in scenarios		
P#	Scenario 1	Scenario 2	Scenario 3	Scenario 1	Scenario 2	Scenario 3
P15	O	O	O	Y	Y	Y
P16	O	O	X	Y	Y	Y
P17	O	O	O	Y	Y	Y(c)
P18	O	O	O	Y(c)	Y	Y(c)
P19	X	O	O	Y	Y	Y(c)
P20	O	O	O	Y	Y	Y
P21	O	O	X	N	Y	Y
P22	O	O	O	Y	Y(c)	N
P23	O	O	O	Y	Y(c)	Y(c)
P24	O	O	O	Y	Y	Y(c)
P25	O	O	O	Y	Y	Y

Table 3. A summary of the scenario-driven user study in Phase 2. (O: suffered the similar experience, X: no suffered the similar experience, Y: yes, N: no, (c): conditional response)

Privacy concerns: Overall, eight subjects and one parent expressed that our service would not create any privacy concerns if the information collected was only used for better diagnosis from their doctors. P20 and P24 raised potential privacy concerns based on geographical location information, but they also agreed to share information with just the doctor. P16 stated that she did not want to expose her sleep behaviors through that sensor data to anyone. P19 was very sensitive to having her biometric information stored on any devices. *"I do not want my personal biometric data to be collected and analyzed somewhere. It makes me feel uncomfortable."*

Part B: Scenario-driven User Study

We also conducted a scenario-driven user study to obtain feedback on the different scenarios that we designed, as well as to determine whether the subjects experienced similar scenarios and service acceptance. The three usage scenarios were based on the opportunities identified in Phase 1. For this step of our study, we individually interviewed the same participants as those in Part A of Phase 2 (10 adult participants and 1 parent of the child with AD). Each interview lasted for approximately 30 minutes and Table 3 summarizes the results.

The scenario-driven study was conducted by having subjects view a separate video for each scenario. Each video first explained a difficulty faced by someone with an itching condition, and then, demonstrated an example of how our service could be leveraged to help control such a problem, which including a demonstration of the smartwatch and smartphone mockup interfaces (Figure 3 and Figure 4). The following three usage scenarios were evaluated.

- **Usage scenario 1:**
  Episode – A patient wants to explain his itching intensity, but the doctor is unable to understand the itching symptom since there are no visible skin lesions.
  Example of Itchtector Usage – The trends in scratching counts/locations shown in Figure 4(a) are provided to help the doctor make a better diagnosis.
- **Usage scenario 2:**
  Episode – A patient asks another patient about how he manages his itching condition. However, he is worried that another person's approach would not necessarily work for him.
  Example of Itchtector Usage – The different trends in

scratching counts related to different management methods are shown, as in Figure 4(b), for better management of their conditions.

- **Usage scenario 3:**
  Episode – A patient cannot determine what factors may be exacerbating their itching condition because there are numerous possible factors such as fine dust, humidity, and geographical locations that could be affecting the patient.
  Example of Itchtector Usage – The sensitivity to certain scratching conditions based on correlation with external factors are shown, as in Figure 4(c), to provide better understanding and help with avoiding exacerbating factors.

Usage scenario 1

Experiences similar to the episode: Nine subjects and one parent had experiences similar to the problem presented in this scenario: (P22)*"When my symptoms were severe at night, I did everything including taking a shower to alleviate my itching. Next day, I visited my doctor and my symptoms had disappeared."* P16 also strongly agreed: *"My allergy reaction mainly appears in the evening. (...) When I visited my doctor, my allergy disappeared."* However, P19 expressed that he did not have any similar experiences since he only visits his doctor when his symptoms are very severe.

Acceptance of the usage example: Nine subjects and one parent agreed with the usefulness of solving the problem in the episode: (P20) *"I think Itchtector would definitely help me convey my itching conditions to the doctors."* P18 raised a question about whether doctors really needed the scratching information or not, while agreeing with the effectiveness of the Itchtector. P21 disagreed with the usage while raising a skeptical question: *"I do not think Itchtector can help discover the reasons for my itching."*

Need for functional modifications: Some subjects (P16, P18, P23, P24) wanted more than four parts (head, arms, trunks, and legs) of their body to be recognized, because their itching locations mainly occurred at folds on their body. In particular, P23 wanted to separate the right and left sides of her body, since whenever her itching was severe, the itching locations often changed from one side to the other.

Usage scenario 2

Experiences similar to the episode: Surprisingly, all the subjects agreed that they have had experiences similar to the episode. They had suffered from trying to find itching management methods that worked for them. For example, P22 stated, *"I did everything that I could for my itching. (...) I even went to a sulfur spa, but my symptoms got worse because of the residue from the sulfur."* P23 also stated, *"I used a moisturizer that my friend recommended, but it did not work for me. I usually try to select a moisturizer based on my experience."*

Acceptance of the usage example: All the subjects showed interest in this particular usage and use of the system to objectively check on their itching condition. In particular, P23 totally agreed with the usage, with the comment: *"It would help me find the management method which is effective for me. (...) If I had Itchtector, I wouldn't have to use other subjective management methods with anxiety."* Interestingly, P22 pointed out that the functions are more appropriate for younger subjects who might not have enough experiences in managing their itching while agreeing with the effectiveness of Itchtector. P23 even suggested a future function: *"It would be good to use the service at home since I really would not want to go outside if my symptoms were severe"*

Need for functional modifications: Some subjects (P18, P20, P25, P22) wanted to add some text to the calendar interface as a reminder, such as a managing method or treatment. P20 stated that since more than two management methods could be used, writing text in the calendar interface would be better. P21 even wanted to share her scratching information with others to find a treatment which fits her.

(a) (b)

Figure 5. (a) Smartwatches used in our study and (b) experiment setting with an infrared camera to evaluate nocturnal scratching.

Usage scenario 3

Experiences similar to the episode: Eight subjects and one parent had experiences similar to the episode. They had difficulty in determining whether some external factors were affecting their itching or not. P23 stated *" I thought that my symptoms became severe when I moved to college. (...) When I came back home, the symptoms did not get better. "* P17 commented about temperature and humidity: *" I first thought that the temperature and humidity did not affect my itching but I am not so sure about that these days."* Interestingly, P15 and P20, who experienced itching symptoms for 25 and 12 years, respectively, pointed out that they didn't even know about new external factors, like fine dust, because the fine dust has only occurred in the last 5 years

Acceptance of the usage example: Nine subjects and one parent agreed with the usefulness of Itchtector. Most of them showed interest in tracking environmental factors such as humidity or fine dust. P23 even wanted to add other environmental sensors, such as for endocrine disruptors for future usages. P19 wanted to use it but also suggested adding other external factors, such as wearing certain clothes, because environmental factors such as temperature could not be controlled by her. However, P22 did not want to use the usage functions because he believed he already understands the environmental factors affecting his itching, based on his long experiences.

Need for functional modifications: Some subjects (P17, P18, P24) raised questions about providing geographical information, while agreeing on the usefulness of tracking temperature, humidity, and fine dust. Because different locations might have many different factors, they felt tracking scratching behaviors based on the location might not be sufficient for understanding the external factors that affect their itching. P19 and P25 suggested that tracking environmental factors such as temperature and humidity for different locations would help determine the impact of location.

PHASE 3: ITCHTECTOR PROTOTYPE

Based on user feedback in Phase 2, an Itchtector prototype was designed, and evaluated through a user study to measure

Subject Information				Diagnosis	Scratch Count
P#	Sex	Age	PO-SCO	(Pruritus)	All (seconds)
P26	F	20	28.3	AD, Allergy	15 (47.6)
P27	F	26	19.6	AD	10 (60.9)
P28	F	22	23.5	Urticaria	41 (126.5)
P29	M	35	34.3	Urticaria, Allergy	26 (133.3)
P30	M	21	15.0	Shingles, Eczema	37 (122.6)
~~P31~~	~~M~~	~~21~~	~~25.3~~	~~AD~~	
P32	M	21	31.0	AD, Eczema	12 (39.6)
P33	F	26	43.2	AD, PS, Angioma	97 (565.6)
P34	M	27	33.5	AD	141 (3337.9)
~~P35~~	~~M~~	~~27~~	~~31.9~~	~~AD~~	
P36	F	19	19.1	AD, Heat rash	43 (141.4)
P37	M	21	12.2	SD	4 (11.7)
P38	F	20	25.9	AD	12 (25.3)
P39	M	24	29.2	AD	62 (550.6)
P40	M	20	16.1	AD, Eczema	39 (142.1)

PO-SCO: Patient-Oriented SCORAD (SCORing Atopic Dermatitis), AD: Atopic dermatitis, SD: Seborrheic dermatitis, PS: Psoriasis

Table 4. List of subjects who participated in Phase 3. In Scratch Count column, 'All' means all scratch events which are labeled with an infrared camera based on medical research [6, 18]. Because of poor video recording quality (P31) and difficulty in analyzing wrist movements hidden by blanket for ground truth analysis (P35), the data collected from P31 and P35 could not be used.

the participants' nocturnal scratching during sleep. For the prototype, an LG Watch Urbane smartwatch was used since it has a relatively low weight and long battery life, compared to other alternative smartwatches. [2] It also supports a gyroscope and linear accelerometer sensors for detecting periodic movements. The gyroscope is used to identify very small scratching behaviors (e.g., scratching with fingers only) while the accelerometer sensor is more effective for sensing scratching behaviors that have high amplitudes.

User Study

The experiment was carried out in the subjects' bedrooms using an infrared camera. To ensure privacy, a researcher (of the same sex as the subject) visits the room to install the infrared camera (Figure 5(b)). Each subject was provided with two smartwatches (one for each wrist) to collect data while the subject was sleeping. The subjects were also requested to sleep for more than 6 hours in order to obtain sufficient amount of data. Table 4 shows the subjects participated in Phase 3.

Once the data was collected, the recorded video was analyzed manually to identify both scratching and non-scratching behaviors. Other meta information was also collected, including start/end time of the scratching behaviors, whether the left or right wrist was involved, and the scratch location. The labeling for each patient was very time-consuming and often lasted up to 10 hours. In addition, two researchers independently labeled sleep movements for cross-validation. Some of the data was excluded if the subject's hand disappeared in the infrared video (e.g., hidden from the blanket) since the ground truth could not be obtained. The sensor data from two smartwatches were synchronized with the video recording to properly correlate the sensor movements with the ground truth.

Scratch Recognition Algorithm

Figure 6 presents a high-level overview of the Itchtector algorithm. The first stage is **Sensing**, where the 3-axis linear-

[2]Other smartwatches or health bands are considered that provide longer battery life and/or lower weight; however, many of the alternatives do not provide direct access to the raw sensor data.

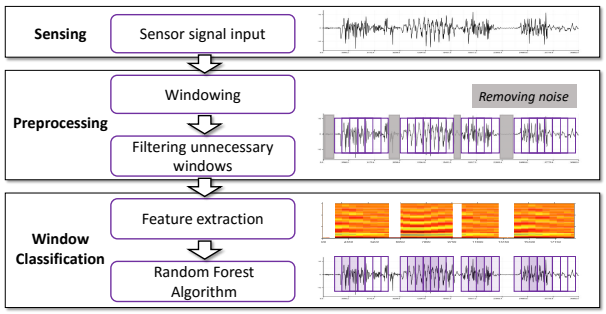
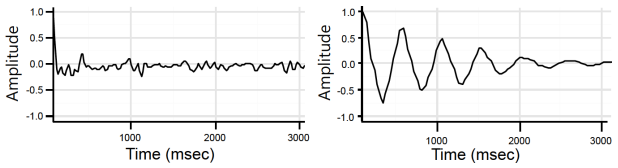


Figure 6. A high-level overview of the algorithm in Itchtector.



(a) (b)

Figure 7. Autocorrelation signals of (a) turning over and (b) nocturnal scratches. Periodic patterns are obviously shown in the autocorrelation signal of real nocturnal scratches.

acceleration and 3-axis gyroscope data are collected at a 50Hz sampling rate. The next stage includes **Preprocessing** and **Window Classification**.

Preprocessing: The first step in the preprocessing is to partition the time-series sensor data into processable units called windows, which are often used in detecting human activities [10, 5]. The windows are shifted by 1 second, such that the last 2 seconds of the current window are used as part of the next window. We also removed windows that had little or no movement since people often spend a significant amount of their time sleeping without movement.

Window Classification: Based on the preprocessed windows, we extracted features reflecting the periodic movement of nocturnal scratching, and these features were used as an input to our machine learning algorithm for detecting windows containing scratching behavior. We first converted the 3-axis sensor data into the 1-axis sensor to reflect orientation-invariant signals as follows:

- *Mag*: The magnitude (i.e., $\sqrt{x(t)^2+y(t)^2+z(t)^2}$) of the 3-axis data, which is used in the previous work [28, 32].
- *PC1*: The first component (*PC1*) after the PCA analysis of the 3-axis sensor data. If the scratching had an obvious direction in the movement, *PC1* will reflect the periodic patterns of the scratching, regardless of wrist orientations.

Then, the two 1-axis signals (*Mag*, *PC1*) from each sensor were converted into the autocorrelation signals. This step was the noise reduction. In this study, we found that the data contained weak periodic signal noises in many places, which were mostly produced by sleep movements such as turning over. To mitigate these noises, we leveraged the autocorrelation function [42] to amplify only periodic signals in the sleep movements, without other non-periodic signals, which enables our classifier to focus only on periodic signals in the movements. An example of the converted autocorrelation signals is shown in Figure 7 for non-periodic and periodic movements. The energy of the periodic fluctuations is measured in the autocorrelation signal; this was inspired by the work to cap-

ture musical rhythmic patterns [26]. The highest peaks and lowest valleys were also extracted to reflect the periodic powers, and prominent/weak peaks were also extracted to reflect the periodicity in the autocorrelation signals [31]. With these features, each window was classified with a random forest algorithm, which is known to be effective in human activity recognition [10].

Scratch Recognition Result

A 10-fold cross-validation [25] was used to evaluate the performance of the Itchtector algorithm. We defined *precision* as the fraction of predicted scratching behaviors that correspond to actual scratching behaviors, and *recall* as the fraction of actual scratching behaviors recognized as scratching behaviors. Overall, our Itchtector algorithm shows the performance for accuracy (nearly 90%), precision (74%) and recall (75%). In this experiment, we observed that the scratch movement are more accurately detected when the movement was continued for a longer time since those movements tend to have clear periodic movements. We leave the comparison of our proposed algorithms with alternative algorithms [28, 32, 39] as future work.

DISCUSSION

In this section, we discuss some of the challenges of the Itchtector system, as well as other possible opportunities and applications.

Challenge 1: Detecting nocturnal scratching: In the nocturnal scratching data that we collected in Phase 3, we observed that some periodic movements during sleep were not necessarily scratching behaviors. For example, continuous leg cramps were identified as periodic movements, and sleep disorders, such as shaking hands in the air, were falsely identified as scratches. In addition, we found that some scratching behaviors do not necessarily show periodic movements. For example, continuous scratching with several body parts moving at the same time did not result in a clear periodic pattern. The algorithm used in Itchtector needs to be improved to decrease both false-positives and false-negatives, and to increase overall accuracy. We also expect that the algorithm can be personalized since each user tends to have differences in their scratching behaviors.

Challenge 2: Extending Itchtector to Field Study: The Itchtector prototype was used to conduct nocturnal scratching evaluations. However, skin conditions often change over a long period of time (e.g., one or two weeks). Thus, a longer field study can provide the historical changes in a patient's condition. Extending this work to a long-term field study presents additional challenges, including the need to improve the energy efficiency of the mobile devices, as well as further improvements in the scratch recognition algorithm, to differentiate other movements during the day time from scratching.

Opportunity 1: Itchtector for Children: The Itchtector system can be very beneficial for young children who suffer from chronic itching conditions. A large proportion of atopic dermatitis patients is children before their 5th birthday [40]. Unlike adults, young children often cannot clearly or accurately communicate their conditions, and often cannot control scratching their body. As a result, Itchtector can be very beneficial to young children and their doctors. However, the smartwatch used for the current prototype is likely too heavy for children. Many of the current smart bands (e.g., Fitbit, Nike Fuelband, etc.) are smaller in size and likely more suitable for children. It remains to be seen if Itchtector can be implemented on these devices.

Opportunity 2: Collaborative data sharing for better management: While this work focused on the treatment of individual patients and their communication with their doctors, another possible application of this work includes extending the services so that subjects can share their information with others, similar to PatientsLikeMe [43]. The absolute amount of scratching might not be directly comparable between patients, since each subject may respond to similar itching symptoms with different amounts of scratching. However, historical data and the relative change in the amount of scratching can be a useful metric to compare across different subjects. Thus, users can explore alternative treatments as well as perhaps better understand which factors aggravate their conditions.

Opportunity 3: Curing psychological fears: We summarized difficulties from Phase 1 into six categories, but we did not consider psychological factors in designing our service. However, as was noted earlier in Phase 2, a few of the participants provided positive feedback, indicating our service could potentially provide some "reassurance" to them by observing their behaviors over an extended period of time and maintaining historical data. In addition, P23 stated that a very serious bout of itching condition that had happened to him, had left a significant mental trauma because of the hardship it caused. Thus, we expect that Itchtector can be extended to help alleviate such psychological concerns for patients.

CONCLUSION

Various skin conditions require proper management or control, to minimize worsening of the condition, and thus, it is important to accurately understand the current condition and how it responds to different medications or changes in the environment. In this work, we present new opportunities with wearable devices for subjects with chronic itching conditions, which can be used to improve how they manage their itching condition, as well as enable better communication with their doctors through more objective feedback. Based on extensive user studies with doctors and subjects with various itching conditions, we designed Itchtector – a wearable-based mobile system that is capable of recognizing scratching behaviors to improve the management of itching conditions. A mockup of the Itchtector was designed and its ability to enhance subjects' effort to manage their itching conditions was evaluated. The Itchtector prototype described and evaluated in this work is the first step in providing an overall system. Both doctors and patients can benefit from having an accurate analysis of the patient's itching condition.

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