Artificial Intelligence in Medicine 69 (2016) 43–52

Contents lists available at ScienceDirect

Artificial Intelligence in Medicine

journal homepage: www.elsevier.com/locate/aiim

A wearable sensor system for medication adherence prediction

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ARTICLE INFO

Article history:
Received 28 October 2015
Received in revised form 19 March 2016
Accepted 23 March 2016

Keywords:
Pervasive computing
Wearable devices
Medication adherence
Deglutition
Piezoelectric sensor

ABSTRACT

Objective: Studies have revealed that non-adherence to prescribed medication can lead to hospital readmissions, clinical complications, and other negative patient outcomes. Though many techniques have been proposed to improve patient adherence rates, they suffer from low accuracy. Our objective is to develop and test a novel system for assessment of medication adherence.
Methods: Recently, several smart pill bottle technologies have been proposed, which can detect when the bottle has been opened, and even when a pill has been retrieved. However, very few systems can determine if the pill is subsequently ingested or discarded. We propose a system for detecting user adherence to medication using a smart necklace, capable of determining if the medication has been ingested based on the skin movement in the lower part of the neck during a swallow. This, coupled with existing medication adherence systems that detect when medicine is removed from the bottle, can detect a broader range of use-cases with respect to medication adherence.
Results: Using Bayesian networks, we were able to correctly classify between chewable vitamins, saliva swallows, medication capsules, speaking, and drinking water, with average precision and recall of 90.17% and 88.9%, respectively. A total of 135 instances were classified from a total of 20 subjects.
Conclusion: Our experimental evaluations confirm the accuracy of the piezoelectric necklace for detecting medicine swallows and disambiguating them from related actions. Further studies in real-world conditions are necessary to evaluate the efficacy of the proposed scheme.

1. Introduction

Prior research has shown that non-adherence to prescribed medications can result in poor patient outcomes [1]. For example, non-compliant schizophrenia patients are at significantly higher risk for depression, arrest, and substance abuse [2]. Generally speaking, non-adherence can result in medical complications, hospital readmissions, and death [3]. Besides the risk of undesirable health outcomes for patients, poor adherence can result in unnecessary healthcare expenses and increased burden on the healthcare system. This issue is also a concern for medical researchers, as patients who choose not to take the appropriate dose of their medication render the assessment of the treatment effectiveness to be much more challenging. Therefore, many methods have been proposed in recent years to address these issues, including pill counts, self-reporting, interviews, and countless interventions intended to increase adherence rates [4–6]. However, these methods are typically associated with low accuracy [7].

Digital technologies that operate with relative transparency to the end user have the potential to improve accuracy compared to manual methods, as issues of human error and intentional misreporting are minimized. Interest in health-monitoring devices have therefore increased significantly in recent years, including activity monitoring approaches such as FitBit and MisFit [8–10].

In the same vein, smart pill-bottles have recently been proposed, which can detect when they have been opened and closed [11,12]. Though this technology can be useful in a number of different circumstances, such as when individuals themselves have no recollection of whether they took their pills, there are several shortcomings associated with this approach. More specifically, there is no definitive information to suggest that the medicine has been ingested after the bottle has been opened.

First, consider a case in which the subject opens the bottle, but is then interrupted by an outside event such as a phone call. Subsequently, the subject may forget to take his or her medication, and would benefit from a reminder a short time later. Furthermore, the

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http://dx.doi.org/10.1016/j.artmed.2016.03.004
0933-3657/

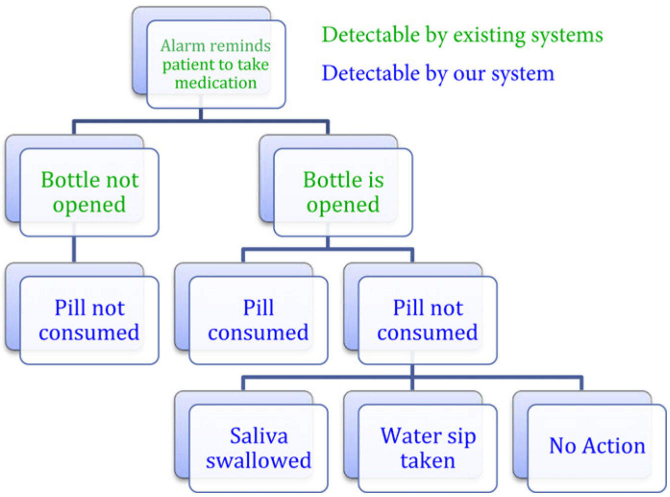

Fig. 1. Different use cases that the system should identify when it is time for a patient to take his or her medication. The capabilities of existing systems are shown in green, while blue includes features unique to our system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

individual may "cheat" the system, by discarding the medication after removing it from the bottle. Lastly, the individual may remove the bottle and, inadvertently or deliberately, take more pills than necessary.

To address these shortcomings, we propose supplementing information from the smart bottle with information from a smart necklace, that can detect when a pill is swallowed using a piezoelectric sensor and associated processing algorithms. The skin motion during the swallow of a medication has a unique pattern that can be used to confirm that the medication has been ingested after the bottle is opened. Data from the necklace is acquired by sampling the piezoelectric sensor strip, which generates a voltage in response to the mechanical stress of deglutition (swallowing). Data acquired from the necklace is transmitted to an Android application for processing using the low-power Bluetooth LE protocol, where classification algorithms are capable of distinguishing between swallowed medication and other types of swallows such as saliva and water. Though this classification is not free of errors, the necklace provides an additional layer of information which can improve detection of noncompliance and provide feedback.

We evaluate adherence based on two different kinds of medicines and supplements: chewables, which are typically targeted towards children in the form of vitamins, asthma medication, Tylenol, and ADHD treatment, and capsules, which are more appropriate for adults. Various use cases are outlined in Fig. 1. Our proposed system extends prior work at ensuring medication adherence; the figures in green represent those steps which cannot be detected with most smart pill boxes.

This paper is organized as follows:

- In Section 2, we describe related work in this field.
- In Section 3, we describe the hardware architecture of the smart necklace.
- In Section 4, we elaborate on the algorithms used to detect medication ingestion.
- In Section 5, we describe the experimental procedure.
- In Section 6, we present our results.
- In Section 7, we discuss the results.
- In Section 8, we provide concluding remarks.

2. Related work

Though many methods of improving adherence have been proposed, a recent survey by McDonald et al. has suggested that even the most effective interventions have failed to provide significant improvements in adherence, though many have managed to make marginal improvements. The various methods fall under two primary categories: indirect and direct methods [13]. Indirect methods include self-reporting, interviews, pill counting, and computerized compliance monitors [14]. Within this category, pill counts and self-reports have shown significant overestimation in user compliance. Direct methods include biological markers, assessment of body fluids, and tracer compounds [15]. As direct methods are generally unsuitable for regular use in home environment, we primarily focus our discussion and comparison on indirect methods.

Several smartphone apps such as MyMedSchedule, MyMeds, and RxmindMe, provide advanced functionality for medication reminders [16–18]. These applications issue reminders, allow users to manually enter their dosage information, and record when they have taken their medication. However, these applications are generally untested, and cannot verify compliance without user involvement [17]. In [19], Sterns et al. mounted a pill bottle onto a personal digital assistant running the RxmindMe software, and successfully trained elderly subjects with an average age of 72 to operate the software used to monitor adherence. This work suggests that users from a variety of age groups and backgrounds have the ability and motivation to use electronic monitoring devices if given adequate training. In [20], Choi et al. explored the topic of user acceptance of neckware-based health monitoring technologies for elderly populations. Their study concluded that there is a strong possibility of seamless adoption of those population groups which suffer from chronic illnesses, particularly if the medication compliance system is incorporated with other health-monitoring features.

Other works propose cell phone reminders and in-home technology to transmit reminder messages, but results are mixed [3,21]. A recent study by Bernocchi et al. [22] characterized the efficacy of home-based telemedicine services for patients with hypertension, using a networked blood pressure monitoring device and regular phone calls from physicians to ensure adherence. The study concluded that telemonitoring of patient adherence can improve patient outcomes.

The "smart blister" has been proposed as a semi-automated, indirect method of assessing adherence. When empty blister cards are returned to the pharmacy, information is scanned and downloaded. This work is a step in the right direction, but the substantial error and lack of real-time features necessitate additional refinements [23]. The work described in [7] describes a portable, wireless-enabled pillbox suitable for elderly and those suffering from dementia. Similar approaches for electronic detection and smart pill boxes have also been proposed [24]. These devices generally suffer from the same shortcoming: they cannot determine if the medication is ingested or simply removed and discarded [25,26].

One notable exception is the recently unveiled plastic sleeve from AMIKO [27], which fits on several standard types of medicine containers and reports if medication has been removed from the bottle using MEMS sensors such accelerometers and gyroscopes. They are also capable of tracking if an inhaler is used, aggregating results on a mobile application. In another work, Valin et al. successfully identified medication adherence using a series of images and associated image processing algorithms [28]. Several other digital systems have been developed for evaluation of swallow disorders and monitoring eating habits [29]. A recent smart bottle technology is the Vitality Glowcap [30]. This smart device can detect when pills are removed, reports information to caregivers,