
Brief Communication

Designing a wrist-worn sensor to improve medication adherence: accommodating diverse user behaviors and technology preferences

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ABSTRACT

Objectives: High medication adherence is important for HIV suppression (antiretroviral therapy) and pre-exposure prophylaxis efficacy. We are developing sensor-based technologies to detect pill-taking gestures, trigger reminders, and generate adherence reports.

Materials and Methods: We collected interview, observation, and questionnaire data from individuals with and at-risk for HIV ($N=17$). We assessed their medication-taking practices and physical actions, and feedback on our initial design.

Results: While participants displayed diverse medication taking practices and physical actions, most (67%) wanted to use the system to receive real-time and summative feedback, and most (69%) wanted to share data with their physicians. Participants preferred reminders via the wrist-worn device or mobile app, and summative feedback via mobile app or email.

Discussion: Adoption of these systems is promising if designs accommodate diverse behaviors and preferences.

Conclusion: Our findings may help improve the accuracy and adoption of the system by accounting for user behaviors, physical actions, and preferences.

Key words: medication adherence, HIV infections, gestures, smartphone, human engineering

INTRODUCTION

“USE-MI” (Unobtrusive Sensing of Medication Intake) is a proof-of-concept, low-cost, and innovative system designed to improve medication-taking measurement and adherence. USE-MI employs a wrist-worn device and a tagged medication container to unobtrusively sense individuals’ gestures related to opening a pill bottle followed by hand-to-mouth arm movement. It uses these data to detect pill-taking behaviors, trigger pill-taking reminders to the wrist-worn

device, and a smartphone app if pill-taking is not detected, and generate summative data on individuals’ adherence levels. To guide the design of this system, we conducted interviews with and observations of, and administered questionnaires to, individuals with and at-risk for HIV. Our goal was to better understand individuals’ current medication-taking practices and technology preferences. Our approach and findings may provide guidance for the development of similar systems.

BACKGROUND AND SIGNIFICANCE

Studies of HIV treatment have demonstrated that durable viral suppression (the optimal outcome) requires consistently high adherence (>90% of pills taken in previous 4 weeks) to antiretroviral therapy (ART).^{1–3} Similarly, when antiretroviral medications are used as pre-exposure prophylaxis (PrEP) in HIV-negative individuals, efficacy is highly dependent on adherence.⁴ For many patients, maintaining high levels of adherence is a challenge and, among both HIV-positive and HIV-negative individuals, self-reported adherence often overestimates adherence compared with more objective indicators.^{5,6} For providers, lack of reliable, real-time information about adherence makes it difficult to identify patients struggling with adherence until adverse outcomes such as treatment resistance or infection have occurred.

Issues around medication adherence extend well beyond ART and PrEP, especially with respect to the management of other complex chronic diseases. Despite significant work developing and evaluating adherence-promoting interventions, Costa⁷ noted in 2015 that the degree of non-adherence had not changed in the previous decade. These adherence-promoting interventions include behavior change, educational, integrated care, self-management, risk communication, and innovative packaging and reminders.⁷ The theories and models on which these interventions are based are vast, including—among others—behavioral learning theory, the health belief model, social cognitive theory, theory of reasoned action, theory of planned behavior, transtheoretical model, and motivational interviewing.^{8,9} Clearly, this is an area where significant work remains.

The vast capabilities and low costs of wearable sensors make them an increasingly viable technology for use in medication adherence-promotion devices for HIV and other patient populations. But, these technologies alone are not sufficient. Any adherence-promoting interventions using these sensors must be based on known theoretical frameworks addressing adherence-promotion more generally. Additionally, research in the area of patient work shows that technology-based intervention outcomes are affected by a complex and evolving sociotechnical system composed of work structures and processes.¹⁰

The proposed sensor-based technologies may support more tailored reminders based on real-time, objective medication-intake data. One research team member showed that a similar approach could detect smoking gestures, and send real-time, tailored messages to the individual.¹¹ Their algorithm detected smoking gestures with high accuracy (96%), precision (91%) and recall (81%).

MATERIALS AND METHODS

Participants ($N=17$) were recruited from two clinics providing medical care and social services for persons living with and at-risk for HIV in Seattle, WA, USA. In semi-structured face-to-face interviews, we asked participants questions about how they stored, took, and remembered to take their medications and audio-recorded their answers. We also elicited their feedback about how two candidate devices (a Microsoft Band and a Sony Android Wear Watch) might support this routine. We then video-recorded participants wearing a wrist device, while taking placebo pills from a bottle. Participants also independently completed an electronic questionnaire assessing their perceived adherence levels, medication-taking practices, preferences for gaining feedback about their medication-taking patterns, and general demographic measures. Interview responses and obser-

vations were coded and reviewed by two team members. Questionnaire responses were analyzed using descriptive statistics. This study was approved by the Swedish Medical Center IRB, and all subjects gave consent for participation. Subjects were compensated with a \$50 grocery store gift card for their time. Table 1 shows how these insights will guide the design of our system.

RESULTS

Shown in Table 2, almost all 17 participants were male, HIV-positive, and taking ART. Most were between 40 and 59 years old, and they were relatively diverse in race/ethnicity. Fifteen of the seventeen participants responded via a visual analog scale what percentage of their anti-HIV medications they think they took over the past 4 weeks.^{12,13} Participants reported taking a median of 95% (average = 88%) of their medications, although 40% of participants reported taking <90% of pills taken in the previous 4 weeks (>90% is considered good). Participants reported taking HIV-related medications once (82%) or twice (18%) per day. Almost all participants took their medications in the morning or at night; only one participant took medications at lunch. Participants reported taking their medications from pill bottles (29%), blister packs (6%), and “pill rolls” with pills heat-sealed into bags labeled with the date and time of prescribed administration (65%). Three participants (18%) reported deviating from their normal method (eg, transferring containers because of travel) five or more days a month. All participants reported taking their medications with liquid; 35% with both liquid and food.

Participants used a range of medication reminder approaches, including placing the medications in visible locations (eg, by the coffee pot) (29%), aspects of the storage method itself (eg, time and date that were stamped on the heat-sealed bags in a “pill roll,”—although some using “pill rolls” were unaware of the date/time stamps on the bags) (12%), annotating calendars or other time-related methods (29%), self-motivation or motivation from others (24%), and eliciting reminders from others (6%).

Participants exhibited varied handedness, with 71% right-handed (RH), 23% left-handed (LH), and 6% ambidextrous. When asked to wear the wrist device and take a placebo pill from a bottle (even if they typically took pills a different way), there was high variability in which hands participants used to perform medication-taking tasks. Figure 1 shows what hands participants used to complete each task, separated by the participants’ handedness. Data for the ambidextrous individual is not shown. A majority (75% of RH, 75% of LH) used their *right hand* to turn the pill bottle cap. Participants were quite evenly split (58.33/41.67% for RH, 50/50% for LH) in terms of which hand they used to put the pill in their mouth. Most participants (83% of RH, 75% of LH) used their *dominant hand* to drink the liquid.

After testing the devices, two participants (12%) stated they would only wear the Microsoft Band and two (12%) stated they would only wear the Android Wear Watch. Most participants (76%) said they would use either device, although 70% of this group preferred the Microsoft Band over the Android Wear Watch. These preferences related to a variety of criteria, including size, comfort, durability, waterproofness to withstand sweating and showering at bathhouses, style, usability of the interface, other functionality available, battery life, and the charging mechanism. One participant did not want a valuable device that might be sold or stolen (eg, to fund stimulant use).

Shown in Figure 2, participants were most interested in receiving medication reminders via the wrist-worn device or a mobile app, somewhat interested in receiving reminders via text messaging.

Table 1. Topics assessed and implications for system design

High-level topic	Sub-topic	How insights will guide design
Current medication-taking process	Perceived medication adherence	Which individuals should be targeted; USE-MI adoption may be higher among poor adherers
	Current medication storage method	What storage methods USE-MI may need to accommodate
	Schedule of medication-taking	Timing and frequency of gesture-recognition and reminders (affects algorithm design and battery life)
	Types of medication dose reminders	Whether USE-MI will support or interfere with current reminder approaches
Physical act of taking medications	Whether medications are taken with liquid or food	Whether the gesture detection algorithms should include liquid or food intake
	Hand(s) used to complete medication-taking actions	Types of gestures needing to be recognized, preferred wrist for wearing device
Feedback regarding the USE-MI system	Preferences for two different wrist-worn devices	Choice of wrist-worn device (Microsoft Band, Sony Android Wear Watch)
	Preferences for reminder method	Choice of reminder method(s) (phone call, email, text, app, on wrist-worn device)
	Preferences for summative medication-taking feedback method	Choice of summative feedback method (email, portal, app) and recipient (self, physician)
	Willingness to adopt the USE-MI system	Tailor USE-MI to persons struggling with adherence to HIV-related medications

Table 2. Participant characteristics

Gender	
Male	16
Female	1
Age range (years)	
20–29	1
30–39	0
40–49	4
50–59	9
60–69	1
Unreported	2
Status	
HIV+ taking ART	16
HIV– taking PrEP	1
Race	
White	7
Black	6
Multiracial	3
Prefer not to answer	1
Hispanic or Latino	
Yes	2
No	13
Prefer not to answer	2

Reminders phone calls and e-mails were not of interest. Most participants (59%) wanted to receive feedback on their pill-taking over time; most (69%) also wanted to share that information with their doctor. Mobile apps (58%) and e-mail (33%) were the preferred mechanisms for receiving this summative feedback. Overall, most participants (67%) stated that they would like to use the system. Some participants felt the feedback would be helpful, but either did not want to wear the device or were concerned about the financial cost of the device.

DISCUSSION

In this study of persons taking HIV-related medications, many reported taking fewer than 90% of their pills in the previous 4 weeks (>90% is considered good) and most expressed interest in

using the system. This combination of clinical need and end-user interest provide support for potential adoption of the proposed system. That said, participants displayed diverse behaviors and had varied preferences for the proposed technologies. We discuss the implications of our findings as they related to the technology *form factors*, gesture-detection *functions*, and end-user *feedback* approaches.

Our proof-of-concept design (Figure 3) employs three physical *form factors*: a wrist-worn device, a smartphone app, and a small motion-detection sensor attached to a pill bottle. Our initial proof-of-concept design requires users to store their medications in pill bottles, as the gestures related to opening a pill bottle are more distinct than opening other medication storage containers. However, in the future we will need to determine how the system could accommodate medication boxes, blister packs, and heat-sealed bags. Our initial system design uses a Microsoft Band—as it better supports implementation of the gesture detection algorithms. Our observations suggest that being able to offer choice among form factors may increase acceptability and adoption.

The observations, interviews and questionnaires gave us insight into how the gesture-detection algorithms will need to *function*. The timing of medications taken (one or twice/day, morning/night) was quite consistent across participants, meaning that we can use this information to anticipate the timing of the gesture-detection and reminders. The limited number of detection timeframes also has positive implications for the battery life of the gesture-detection sensors. The finding that all individuals took their medications with liquid allows us the possibility of adding this gesture to the detection algorithm. The significant variability in what hands individuals use to perform medication-taking gestures presents a significant design challenge. Regardless of handedness, most individuals turned the bottle cap with their right hand, were evenly split on what hand they used to put the pill in their mouth, and tended to drink water with their dominant hand. This finding suggests we cannot reliably detect medication taking using a single gesture. The most complex scenario is a right-handed individual wearing the device on their left wrist, as they are unlikely to turn the bottle cap or drink water with their left hand. For this group, a motion-detection sensor directly on the bottle is especially important.

Finally, there was some diversity in participants' preferences for system *feedback* mechanisms, namely how they receive medication-taking reminders and summative reports. The current

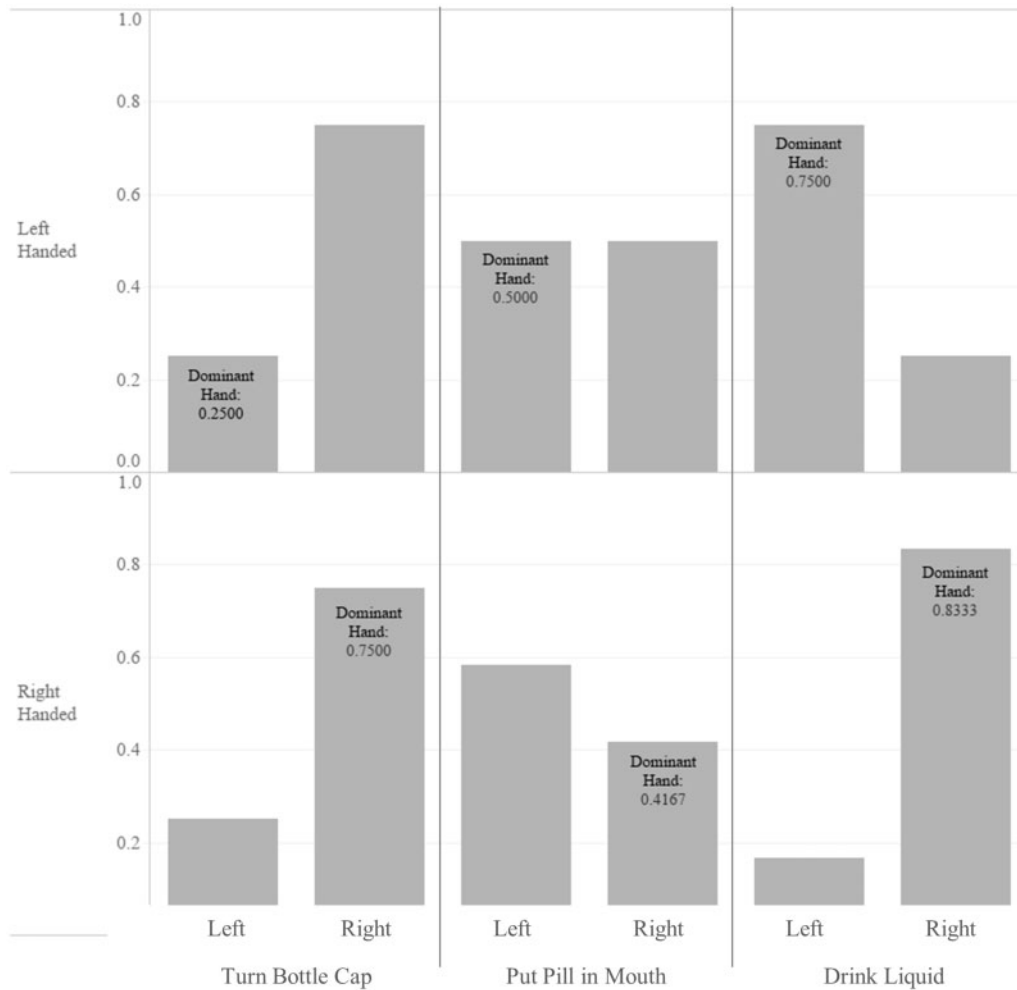


Figure 1. Hands used to complete medication-taking tasks.

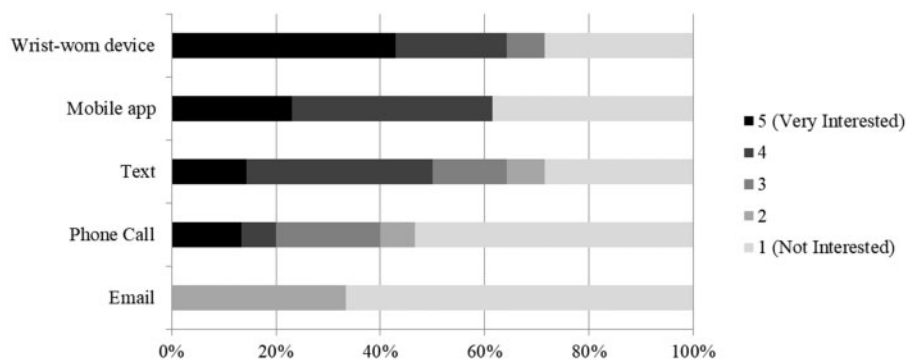


Figure 2. Reminder preferences.

system design sends medication-taking reminders directly to the wrist-worn device and to the smartphone app (the two most preferred methods). Summative reports can be viewed from within the smartphone app (the most preferred method). While these align with participants' stated preferences, future iterations of the system will ideally allow some flexibility in these methods. Participants also noted a desire to share the summative reports with their physicians; the system will

therefore have the capacity to generate and send reports to the participants' physicians.

While a large proportion of our sample of participants used pills stored in heat-sealed bags (ie, "pill rolls"), we believe this practice is uncommon based on a larger online survey ($n = 96$) we conducted. In that survey, 2% of respondents used pill rolls. This large proportion of our participants was likely due to two nearby community

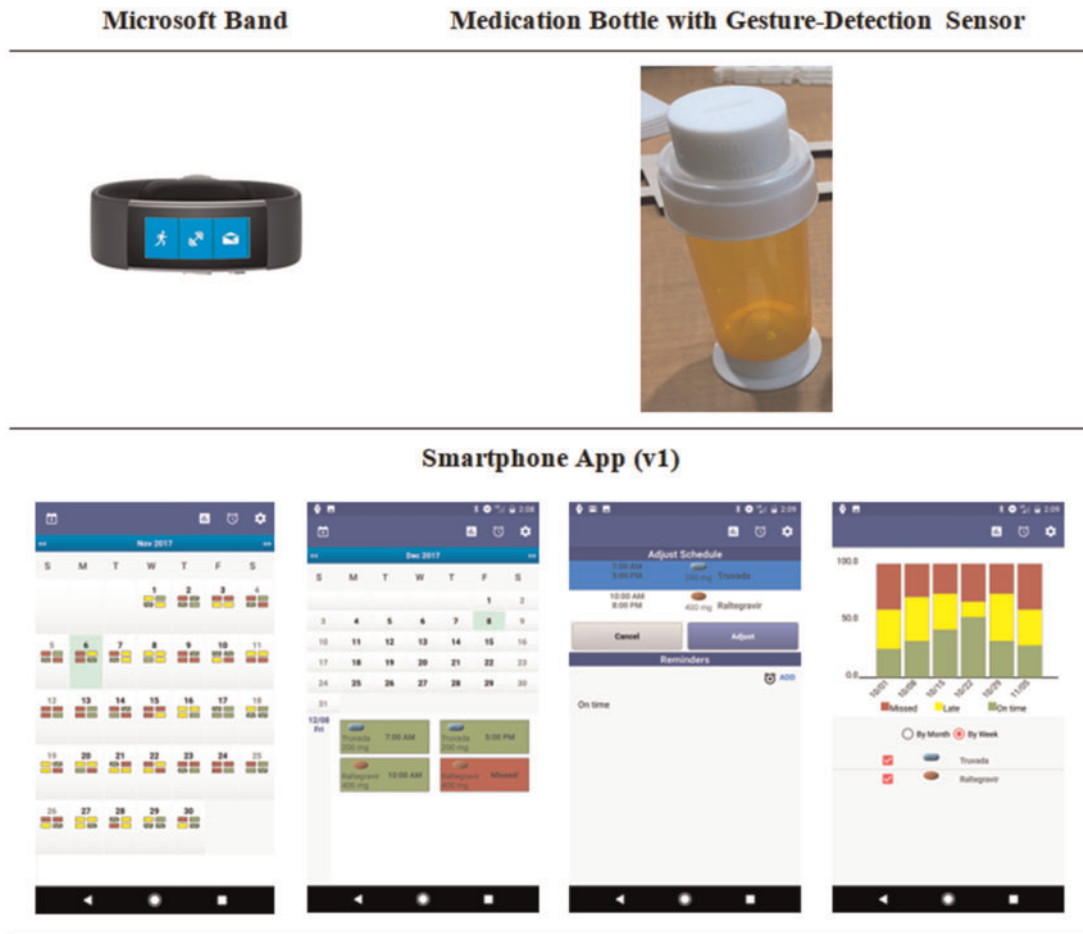


Figure 3. USE-MI system components.

pharmacies preferring to use pill rolls. We expect that in other populations, particularly for persons on PrEP, a higher portion of individuals would use pill bottles. Fifty-percent of PrEP survey respondents used pill bottles. This is an important variable to assess in a potential user population.

Our future work will include a pilot validation study, where participants will use the system for six months. This study will allow us to better understand and improve the accuracy and efficiency of the sensors and detection algorithms. We will also be able to understand patterns of adoption and use of the system, including how we can re-design the system to make it more useful and usable.

CONCLUSION

To ensure adoption, interventions using sensor-based technologies must account for user behaviors, physical actions, and preferences. While we focused on designing an intervention for individuals with and at risk for HIV, our findings may align with the preferences and behaviors of patient populations with many other medical conditions for which medication adherence is critical.

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Conflict of interest statement. None declared.

CONTRIBUTORS

All authors conceived of and designed the study. BS conducted participant interviews. JM, SK, and VM analyzed the interview data. JM drafted the manuscript. All authors made critical manuscript revisions, and approved the final version for submission.

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