

Energy-Efficient Monitoring of Potential Side Effects from COVID-19 Vaccines

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Abstract—COVID-19 has affected the world for almost two years causing lots of damages and losses of lives. With the development of sensing technology and digital health, recent research studies suggest to use wearable devices for monitoring COVID-19 symptoms or analyzing people's behaviour change. As COVID-19 vaccines are getting widely available, their side effects have raised public concerns, though have not yet been thoroughly studied due to the short deployment time. As far as we know, this work is the first study to use wearable devices and mobile app to collect physiological data to explore potential side effects to human bodies from COVID-19 vaccinations. We designed and developed a mobile sensing system, which can monitor changes of physiological indicators through wearable devices, collect self-reported data from the users and proposed a green data transmission mechanism which can reduce the communication overheads. Pilot study has been conducted to evaluate the feasibility of our system. Preliminary results show that increased resting heart rate (RHR) and changes on average heart rate (HR) are observed in some participants after COVID-19 vaccinations. This study opens up the opportunity to collect larger amount of data and further investigate potential side effects from COVID-19 vaccinations.

Index Terms—Internet-of-Things, wearable devices, COVID-19, energy-efficient transmission

I. INTRODUCTION

Since the outbreak of a novel Coronavirus Disease 2019 (COVID-19), the virus has been widely spread around the world causing significant losses of lives and damages. COVID-19 was first recognized in December 2019, which can cause severe acute respiratory syndrome. Up to 9 July 2021, more than 185 million confirmed cases of COVID-19 globally, including 4 million deaths, have been reported to World Health Organization (WHO). As of 7 July 2021, more than 3 billion vaccine doses have been administered [1]. The world still experiences around 400k daily new cases in early July 2021, which reflects that the pandemic is yet to be over.

Recently, a new variant of COVID-19, named Delta variant, is found to be more infectious [2]. Preventing another wave of global outbreak is both important and challenging. Droplets transmission is believed to be the main source of COVID-19 transmission in human beings. People who have close contact (within 6 feet) with confirmed cases and without protective measures have high risk of infection [3]. Social distancing measures and wearing masks are shown to be effective to reduce the risk of transmission. Meanwhile, many scientists

have spent a lot of effort to develop vaccines against COVID-19. Under normal circumstances, vaccine development is a long and complex process, often taking ten to fifteen years [4]. However, it took around one year only to develop various COVID-19 vaccines for clinical trials in this emergency COVID-19 situation. Many people reported feeling unwell or having side effects after taking the COVID-19 vaccines, which has raised public concerns and caused vaccine hesitations.

Identifying side effects of vaccines is difficult, time consuming, and requires a lot of clinical trials that involve thousands of volunteers from different age and sex groups. The volunteers have to stay in hospital to measure vital indicators of their bodies, such as heart rate, body temperature, breathing pattern, and blood oxygen level. Scientists will collect and analyze the data before and after vaccinations to understand the effects of the vaccines to human bodies. In terms of COVID-19 vaccines, some vaccines were put into use before completing large-scale clinical trials. Thus, it is important to collect data from large amount of people who have been vaccinated to study potential side effects of COVID-19 vaccines. However, it is not practical for every citizen to stay in hospital after vaccination. Using wearable devices, such as Fitbit trackers and Apple Watches, can help to collect vital signs from a large population.

Fitbit trackers and Apple watches are examples of wearable devices integrated with many sensors. For instance, a Fitbit Charge 4 wristband can measure heart rate, activity level, sleep quality, and body temperature [5], which make these kinds of devices ideal for monitoring human body's physiological features outside the hospital. Wearable devices have also been used in studying many different medical problems [6]. In this paper, we proposed a data collection and monitoring system to measure potential side effects from vaccinations based on wearable devices and mobile application. The proposed system will monitor users' vital signs through smartwatches or smart wristbands, using energy-efficient mechanism to transmit the sensor data to the cloud server. In addition, a mobile app will send survey forms to the users and collect their symptom reports. Data analytic algorithms will extract the vital signs and patterns to detect any potential side effects from vaccinations.

II. RELATED WORK

With the development of Internet-of-Things (IoT) and artificial intelligence, digital health has attracted a lot of attention.

Making use of wearable devices in digital health has already shown great potential in a wide range of applications. The wearable devices can provide 24/7 data collection capabilities, which are unobtrusive and efficient [6]. Scientists can use a simple app to analyse the gait using the accelerometer data provided by a smartwatch or a smart wristband, which can detect the symptoms of Parkinson's disease called gait frozen and perform early detection [7].

In addition to the disease-specific or clinical applications mentioned above, wearable devices has great potential for fighting against the pandemics. Radin et al. [8] used wearable devices to collect resting heart rate (RHR) and sleep data to detect flu infection. They observed that acute infection can cause physiological responses (e.g. increased heart rate) of the human body. The COVID-19 pandemic has caused overloading of the healthcare systems worldwide. By using consumer wearable devices, mass health monitoring can be done easily and cost-effectively. Hedayatipour et al. [9] indicated that the pandemics in the last 100 years share some similar symptoms that can be detected by ordinary wearable devices, such as smartwatches. Karthickraja et al. [10] used wearable sensors and IoT devices to measure respiratory rate, oxygen saturation (SpO2), and temperature; and discovered changes when the subjects were exposed to the virus.

During COVID-19 pandemic, contact tracing and social distancing measures are successful in controlling the spread of the COVID-19 virus. Sun et al. [11] proposed a system based on smartwatches and smartphones to collect location data, physiological data, phone unlock duration, and social app use duration for analysing the social behaviours during pandemic lockdown. Jahmunah et al. [12] analysed various digital tools from different countries and regions; and conducted research on different wearable devices. They concluded that wearable devices can definitely help to handle health crises in the future.

Current diagnosis methods may not work if a patient has just been infected and the symptoms were not obvious to be observed. Wearable devices can be used to monitor symptoms and collect physiological data in large number of susceptible people. They can be used to identify asymptomatic or pre-symptomatic COVID-19 cases. Smarr et al. [13] used smart wearable devices to monitor continuous fever caused by COVID-19. Mishra et al. [14] can detect infection before symptoms onset up to nine days using the resting heart rate (RHR) measured by Apple Watch. Wong et al. [15] used wearable biosensors to continuously monitor vital signs of personnel being quarantined. Since COVID-19 virus will trigger immune responses in human body, analysis of these data can support early detection of infections. For example, heart rate variability (HRV) can be used for early detection of COVID-19. Miller et al. [16] conducted a study using WHOOP strap to measure respiratory rate, RHR, and HRV for COVID-19 early detection.

Studying the side effects from vaccinations is difficult. The term side effect means that we understand there is a direct linkage between the vaccines and the adverse events. In most cases, we can only study adverse events after occurrence, while

no lab testing data are available to prove the side effects or linkage. Currently, there are a number of reporting systems like EudraVigilance [17] from European Medicines Agency, which is used to study adverse events at a statistical level. There are also research studies using online questionnaires to collect user-reported adverse reactions. Menni et al. [18] used a mobile app to collect symptom reports within eight days after vaccination in order to study the adverse events on a statistical level. Wearable based digital health solutions have great potential to collect massive data which may help to prove the linkage in this active vaccination period. As far as we know, our work is the first study proposed to use smartwatches and smart wristbands to measure potential side effects from COVID-19 vaccines.

III. PROPOSED SYSTEM

We present our system design and the procedures of data collection and data analysis in this section.

A. System Design

We designed and developed a multimodal mobile sensing system based on wearable devices and mobile phones to collect and analyse the physiological data and self-reported data from the users. Fig. 1 shows the design of our system architecture. The proposed system includes a custom mobile application, called "BeatCOVID", which can distribute survey forms to the users and collect their reports on sickness, vaccination records, etc. The mobile app and the survey forms handle the data anonymously and will not reveal the identify of the users. We do not collect and store any personal identifier or information that can be used to identify individuals. The system can collect physiological data, such as heart rate, activity level, and sleep quality from the wearable devices. The information is obtained based on the multi-dimensional sensor data from the wearable devices, including the 3-axis accelerometer, optical heart rate sensor, GPS, temperature sensor, vibration sensor, red and infrared sensors for blood oxygen saturation monitoring, etc. All the data from the users are encrypted and stored on our secured servers with security measures. Currently, we have implemented and experimented our system with Android phones and Fitbit smart wristbands. We have also compared our data with Apple Watch.

B. Data Collection

Heart rate (HR) data are currently taken every five seconds and measured in beats per minute (BPM) in our system. We collect the sensor data starting from eight days before the first shot to seven days after the second shot in our pilot testing. The data is formatted into CSV files. The activity data includes activity level, time period, and number of steps per minute. Sleep records contain time and duration of sleep and the stage of sleep.

Survey forms are distributed through the "BeatCOVID" mobile app, which allows the participants to fill in self-reported data in three different types. Participants who are enrolled in the study will first read a consent document and

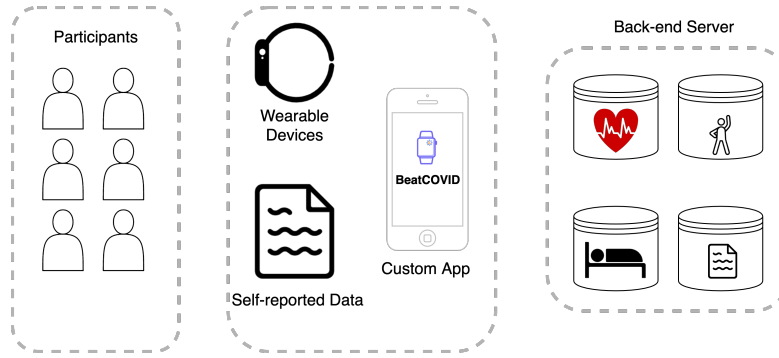


Fig. 1. We designed and developed a mobile sensing system with wearable devices to collect physiological data from the participants. The system monitors physiological changes and provides data analysis through a custom mobile application and a back-end server. The custom mobile app, called “BeatCOVID”, can collect sensor data generated by wearable devices and distribute survey forms to the participants to collect their self-reported data.

give their consent. They will fill in a background survey collecting their demographic information and brief medical history. The second form is the daily symptom survey, in which the participants can fill in daily to report sickness or reactions, if any. The participants are also required to report their vaccination dates and COVID-19 test results, if any. All these data are completely anonymous.

C. Data Transmission

Normally, these heart rate and physiology data collected by smart watches are first transmitted to the mobile phone first via bluetooth, then they are passed to the cloud server using TCP connection by the corresponding application on the phone. The data from the smart watches are sampled every 5 seconds. If the app sends one record per packet, it will definitely waste a lot of bandwidth because of the overhead of the packet header. In our system this problem is particularly serious, since one record only contains two 4-byte integers (the heart rate and the step count) and a 8-byte timestamp which is even smaller than the header size. Normally, a developer will include multiple records in one packet before sending the data to the server, which can provide more energy-efficient data transmission.

From our observation, it is common to obtain the same sensor measurements in a short period of time. Thus, we propose a compression scheme to remove redundant data before transmitting the data to the server. The server can decompress the data after receiving the data packets. We develop an algorithm to detect consecutive and identical sensor measurements and compress them by showing how many times the previous measurement has been repeated. For example, consider a sequence “72 72 72 73 71 71 71 72 73” with five measurements, our algorithm will compress them into “72 %3% 73 71 %3% 72 73”, which we can pack more measurements into one single package. Based on our analysis, our algorithm can reduce 30% of the redundant data in data transmission.

D. Data Analysis

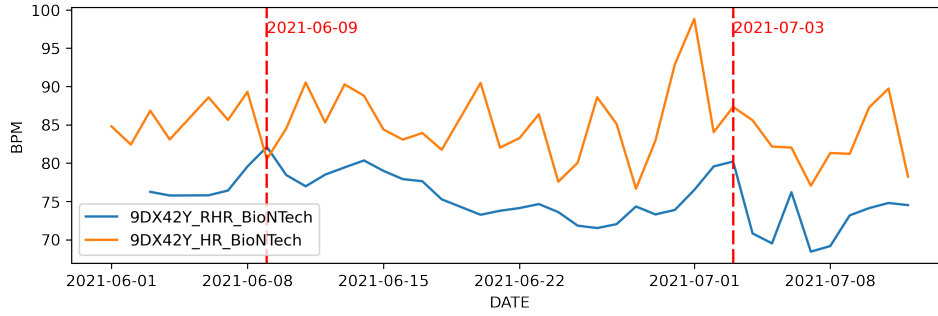
1) *Fitbit Data*: Once the user consent is given, the app can collect physiological data through the APIs. Heart rate data

contains measurements every five seconds and activity level data contains number of steps per minute. Note that Fitbit measures Resting Heart Rate (RHR) and Heart Rate Variability (HRV) only during sleep. However, some participants we recruited did not wear Fitbit during sleep, so we calculate the RHR based on their heart rate data in the daytime. We take the time periods with zero steps for over 12 minutes to calculate the RHR following Mishra’s work [14]. Then, the RHR data are averaged to a daily value. Besides, we also calculate the daily average HR based on the raw heart rate data.

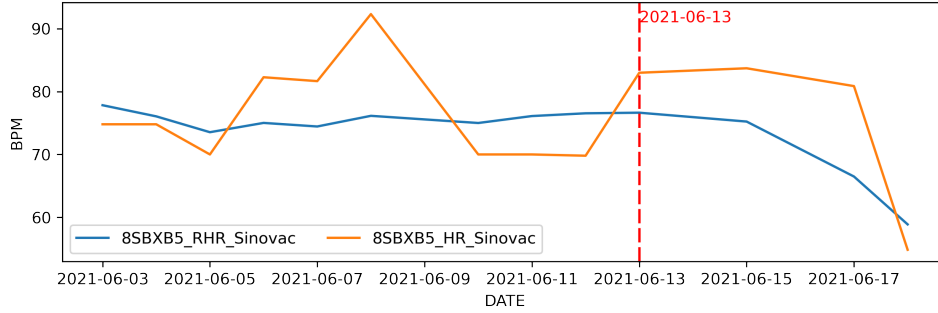
2) *Apple Data*: We included an Apple Watch Series 6 in our pilot testing. The Apple watch can measure HR, RHR, and HRV. RHR and HRV can be accessed by Apple Health. RHR data is measured in a daily level, while HRV is measured at six random times each day. The heart rate data, measured in minute level, is calculated by an adaptive sampling rate algorithm.

IV. PILOT STUDY

The way how COVID-19 vaccines work is similar to how our bodies fight illness. When the virus that causes COVID-19 invade our bodies, they attack and multiply. This invasion, called an infection, is what causes illness. Our immune system uses several tools to fight infection. Once vaccines have been injected into human body, the immune system will start to respond. The responding symptoms may be similar to those caused by COVID-19 infection. Based on the study on COVID-19 symptoms, we make an hypothesis that it may be possible to detect changes on physiological indicators, such as increased heart rates, which could be captured by the wearable devices. We are interested in monitoring any changes of physiological indicators that may be related to COVID-19 vaccines. For example, since April 2021, there have been more than a thousand reports to the Vaccine Adverse Event Reporting System (VAERS) of cases of inflammation of the heart, called myocarditis and pericarditis, happening after mRNA COVID-19 vaccination (i.e., Pfizer-BioNTech, Moderna) in the United States. We believe that collecting more data from the wearable devices may be useful for studying related issues.



(a) HR and RHR of Subject 9DX42Y from Fitbit



(b) HR and RHR of Subject 8SBXB5 from Fitbit

Fig. 2. Fitbit data of two subjects. Subject 9DX42Y was the earliest recruited subject. The monitoring period was between 1 June 2021 and 12 July 2021 and the brand of vaccines was Pfizer-BioNTech. Subject 9DX42Y took the first shot on 9 June 2021 and the second shot on 3 July 2021. As shown in Fig. 2(a), the RHR of subject 9DX42Y went up on both vaccination dates while the changes in daily average HR vary. Subject 8SBXB5 took his first Sinovac shot on 13 June 2021. The data after 18 June 2021 from his Fitbit Charge 4 is incomplete. The subject switched to an Apple Watch on 16 June 2021. There was no significant change in the HR and RHR of subject 8SBXB5 after the first injection.

A. Experiment Setup

In this preliminary study, the main goal is to explore the potential and feasibility of detecting any changes of physiological indicators after taking COVID-19 vaccinations. We have recruited six participants from different ages and genders randomly among our colleagues and friends in June 2021. We gave each of them a Fitbit Charge 4 tracker at least seven days before they received their first COVID-19 vaccine. Participants were asked to wear their smart wristbands as much as possible. We encouraged them not to remove the tracker unless it must be charged. All participants were asked to report their sickness daily, if any, through our custom app. The data collection period would end seven days after the second dose of their COVID-19 vaccination.

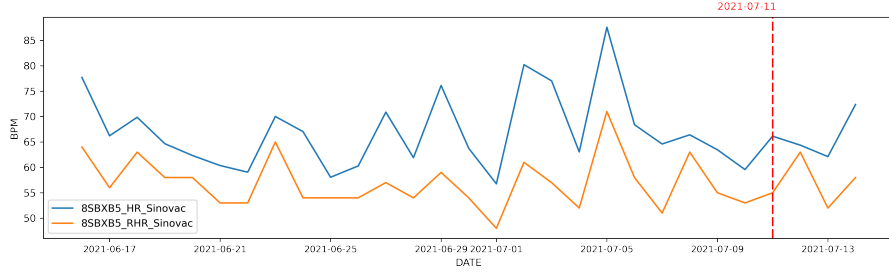
B. Preliminary Results

We present the preliminary results from our pilot study in the following. We focus on the heart rate (HR), resting heart rate (RHR), and heart rate variability (HRV) in this analysis as we found some interesting observations. We selected the results of two users who have completed two doses of COVID-19 vaccinations. One subject has taken two shots of Pfizer-BioNTech vaccines; another has taken two shots of Sinovac vaccines.

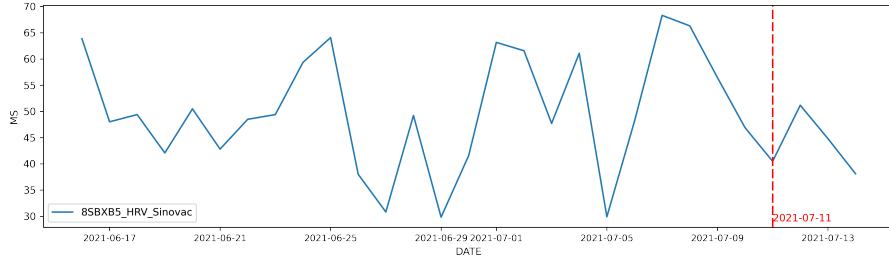
1) *Fitbit Results:* We present the data of subject 9DX42Y, who has taken the Pfizer-BioNTech vaccines; and another

subject 8SBXB5, who has taken the Sinovac vaccines. The data collection period of subject 9DX42Y was between 1 June 2021 and 12 July 2021. He took his first dose on 9 June 2021 and the second dose on 3 July 2021. During the whole period, this subject wore a Fitbit Charge 4 almost all the time, except charging the tracker and during sleep. The data collection period of subject 8SBXB5 was between 3 June 2021 and 18 July 2021. He took his first shot on 13 June 2021 and second shot on 11 July 2021.

The result of subject 9DX42Y is shown in Fig. 2(a). The figure shows the daily average heart rate (HR) and the resting heart rate (RHR) of the subjects. We can see significant changes in both HR and RHR after both doses of vaccination. RHR went up quite obviously on both vaccination dates, while the changes of average daily HR vary. The subject also reported that he had experienced arm pain during the first 72 hours after the vaccinations via the mobile app. His average daily heart rate was slightly lower on the vaccination dates and the day after compared with the previous few days. This may be due to the fact that the subject intended to take more rest and become less active after the vaccinations. This observation was consistent with the subject's report on experiencing fatigue via the mobile app. On the contrary, the result of subject 8SBXB5 was not obvious as shown in Fig. 2(b). There was no significant changes on his HR and RHR. Subject 8SBXB5 also did not report any sickness or reactions through the mobile



(a) RHR and HR of Subject 8SBXB5 from Apple Watch



(b) HRV of Subject 8SBXB5 from Apple Watch

Fig. 3. Data from the Apple Watch during the monitoring period between 16 June 2021 and 14 July 2021. Subject 8SBXB5 started wearing an Apple Watch on 16 June 2021. He took the second Sinovac shot on 11 July 2021. We can see that both RHR and HR are slightly higher after the second shot, while HRV is lower compared with the previous few days.

app.

2) *Apple Results*: Subject 8SBXB5 has started wearing an Apple Watch Series 6 since 16 June 2021, three days after his first dose vaccination. He took his second dose on 11 July 2021. As shown in Fig. 3, we observed a slight increase on RHR and HR compared with the day before. However, when comparing the readings with previous three weeks, we cannot observe any significant changes or pattern. Similarly, we observe a drop on HRV on 11 July 2021 compared with the previous few days.

V. FUTURE STUDY

We plan to recruit larger number of participants in the next stage of our experiments. We will lower the age range of our target group from age 18 to age 12, since Hong Kong government starts encouraging youngsters at 12 or above to take COVID-19 vaccinations. The new age range from 12 to 60 in our study has already been approved by the ethics committee of the University of Hong Kong. We are now recruiting participants through two channels. We recruit participants who are between 12 and 16 years old through secondary schools. We recruit participants aged 18 or above from the general public. Apple Watches and Fitbit trackers will be supported for data collection in our experiments. We would also like to explore data compression methods to further reduce the communication overheads.

VI. CONCLUSIONS

In conclusion, we have designed and developed an energy-efficient mobile sensing system to collect and analyse physiological data from wearable devices and a custom mobile

app, called “BeatCOVID”. We have conducted a pilot study to test the functionality and feasibility of the proposed system in detecting potential changes on physiological data after COVID-19 vaccinations. From the preliminary results, we find that it is possible to observe an unusual increase of resting heart rate and changes on average daily heart rate in some participants. Our mobile app is found to be effective for the users to report any sickness or reactions after taking COVID-19 vaccinations. Besides, our proposed data transmission mechanism can reduce 30% of the redundant sensor data. For the future, we will extend our study to collect and analyse data from a larger population. We plan to recruit more participants and hope to contribute to understanding potential side effects on human bodies from COVID-19 vaccines.

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