Preview of Award 2029520 - Annual Project Report

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Federal Agency and Organization Element to Which Report is Submitted:	4900
Federal Grant or Other Identifying Number Assigned by Agency:	2029520
Project Title:	RAPID: In-Home Automated and Non-Invasive Evaluation of COVID-19 Infection with Commodity Smartphones
PD/PI Name:	Wei Gao, Principal Investigator Wei Chen, Co-Principal Investigator Erick Forno, Co-Principal Investigator Heng Huang, Co-Principal Investigator
Recipient Organization:	University of Pittsburgh
Project/Grant Period:	07/01/2020 - 06/30/2022
Reporting Period:	07/01/2020 - 06/30/2021
Submitting Official (if other than PD\PI):	N/A
Submission Date:	N/A
Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions)	N/A

Accomplishments

*** What are the major goals of the project?**

The key to combat the COVID-19 pandemic is to prevent the pandemic from overloading the public healthcare system, so that sufficient medical resources could be available for hospitalized patients being infected. To avoid such overload, false positives of COVID-19 infection should be detected out of clinic, to avoid unnecessary hospital visits as many as possible. Such detection, however, is difficult because COVID-19 shares many symptoms in common with other diseases, such as ear infection that causes fever and respiration diseases that cause shortness of breath.

The goal of this research is to address the aforementioned difficulty by developing new mobile sensing and AI techniques that use commodity smartphones to measure the changes of humans' airway mechanics, which are uniquely correlated to COVID-19 infection. More specifically, since COVID-19 infection causes pathological changes of lung alveoli and bronchi, it could result in narrowed bronchi, airway inflammation and mucus that can be used as more reliable indicators to evaluate such infection. We propose to measure these indicators by transmitting acoustic signals with the smartphones' built-in speakers and analyzing the received acoustic signal after it is being reflected by the airway. We aim to ensure accuracy, reliability and generality of these measurements over actual human bodies. First, we will design new acoustic waveforms to minimize the distortion of acoustic signal when being propagated throughout the human airway system. Second, we will develop new signal processing techniques to appropriately analyze the received signal and evaluate the change of mechanics throughout the entire human airway system. Third, to ensure that our proposed technique can be widely applied to big crowds of people, we will use deep learning techniques to develop generic models that depict the core characteristics of humans' airway mechanics. The proposed technologies will be implemented and evaluated by both lab-controlled testing and medium-scale experimentation with student volunteers.

*** What was accomplished under these goals and objectives (you must provide information for at least one of the 4 categories below)?**

Major Activities:

During the past year, we are striving to develop new mobile sensing and AI techniques that allow commodity smartphones to perform accurate and low-cost spirometry tests, when being hand held by the patients themselves at home. In addition, we also developed a mobile sensing system that allow commodity smartphones to objectively evaluate patients' possible muscle fatigue, which has also been proved to be related to certain COVID-19 symptoms.

First, we made research efforts to allow accurate, convenient and low-cost spirometry tests at home by patients themselves, using commodity smartphones. This capability would be useful to dramatically alleviate the burden of public healthcare system with the burst of patient needs, and hence make important contributions to combating the COVID-19 pandemic. Spirometry, as the most commonly used pulmonary function testing (PFT), assesses such obstruction by measuring the volume and velocity of breathing airflow, and is crucial in pulmonary disease evaluation and monitoring. Ideally, spirometry should be daily conducted out of clinic, to timely detect and avoid frequent disease exacerbations that cause emergency department visits or hospitalizations. However, current spirometers in clinic are too bulky for daily home use. Recent efforts reduce the size of spirometers but their costs (>$2,000) are still too high for home use. Low-cost spirometers priced at <$100 are mostly inaccurate and could produce >20% error. To reduce the cost of portable spirometers without impairing the PFT accuracy, researchers developed wearable sensing systems, but required attaching extra hardware to human bodies. We developed a new technique called SpiroSonic, a novel system design that uses commodity smartphones to support complete, accurate yet reliable spirometry tests out of clinic, with various environmental and human factors. Our design builds on the close correlation between lung function and chest wall motion of humans, which has been widely validated in clinical practice. SpiroSonic measures chest wall motion as an externally observable biomarker, and interprets such motion into lung function indices. To measure such motion, SpiroSonic transmits ultrasound signal with the smartphone's speaker, and analyzes the signal being reflected by the patient's chest wall and received by the smartphone's microphone. In this way, SpiroSonic is 100% contactless and non-intrusive. In practice, to ensure accurate tests when being hand held by the user, we identify and eliminate the impacts of the user's hand and body motions. To identify the impact of these motions, we convert the received signal to I/Q traces on the complex plane1, so as to quantify such impact as the geometric distortions of I/Q trace. Then, we adaptively remove such impact by correcting these distortions and calibrating the received signal as if it is produced with a stationary smartphone. After that, the acoustic signal measurements are being correlated to the user's lung function indices through a Bayesian regularized neural network.

Second, we also aim to support objective evaluation of muscle fatigue on commodity smartphones. The muscle fatigue and pain have been proved to be indicators of early-stage COVID-19 infections in many cases. During clinical visits, the muscle fatigue can be evaluated by lactic acid accumulation using a blood test or myoelectric signals using electromyography (EMG), but frequent daily evaluation of muscle fatigue out of clinic is usually preferred in most of muscular disease diagnosis for long-term tracking of disease progress and medication efficacy. Unfortunately, effective methods for such out-of-clinic evaluation are currently missing, and patients instead are only asked to self report their feelings of fatigue by completing certain questionnaires. To address this challenge, we developed MyoMonitor, a new technique that uses commodity smartphones for objective muscle evaluation out of clinic. This technique is built on the physiological fact that human muscles will unconsciously tremble or shake when getting fatigued and such tremor proportionates to the level of muscle fatigue. Since this muscle tremor can produce shape changes on the muscle surface, we could measure the muscle fatigue from such changes which affect the acoustic signal being transmitted between the smartphone's built-in speaker and microphone. In practice, to ensure the accuracy and reliability of evaluating muscle fatigue, our design aims to address multiple technical challenges, including 1) As the built-in speakers of commodity smartphones are usually omnidirectional, the transmitted acoustic channel is significantly affected by the motions of other parts of the human body (e.g., head and hands); 2) We need to appropriately interpret the disturbances on the acoustic channel into quantified levels of muscle fatigue, so that we have numerical metrics of fatigue level for fatigability analysis. 3) We lack quantifiable ground truth of muscle fatigue, and we must find ways to prove that our measurements are consistent with fatigue practices.

Education Activities:

Some of the research results have been integrated with the education curricula at University of Pittsburgh. For example, the research outcome on supporting spirometry tests on commodity smartphones (published at ACM MobiCom 2020) has been integrated into the curriculum of the course "ECE1175: Embedded Systems Design", towards multiple course projects for undergraduate students to practice their hands-on system building skills.

Outreach Activities:

The PIs have been actively involving minority and underrepresented groups of students into research. During the past year, PI Gao was supervising one female undergraduate student (Alana Dee) on mobile sensing research, and also participated in the Hot Metal Bridge (HMB) program at Pitt, which offers a post-baccalaureate fellowship to minority students. He mentored several HMB fellows and introduced them to the research area of mobile sensing and computing.

Specific Objectives:

This research project aims to develop new mobile sensing and AI techniques that enable low-cost self-evaluation of possible COVID-19 infections at home using commodity smartphones. Our technique builds on the unique correlation between COVID-19 infection and change of humans' airway mechanics. COVID-19 infection causes pathological changes of lung alveoli and bronchi, and results in narrowed bronchi, airway inflammation and mucus that can be used as more reliable indicators to evaluate such infection. To measure these indicators, a smartphone is mounted to a funnel-shaped mouthpiece, and we use the phone's bottom speaker and microphone to transmit and receive acoustic signal during normal breath. Such signal will be reflected by airway lumens when traveling in airway, and will be analyzed to measure airway mechanics. To ensure the accuracy, reliability and generality of measurements over actual human bodies, three research tasks are planned:

Task 1: Acoustic Waveform Development. To precisely evaluate the airway mechanics, the acoustic signal should travel through the whole airway and reach the lung bronchi, but may be largely distorted in between. To minimize such distortion with the commodity smartphones' hardware, we will use short-time frequency modulated continuous wave (FMCW) signal pulses to maximize the signal bandwidth, and further apply a Hanning window to avoid unwanted frequency components being produced by such distortion.

Task 2: Informative Signal Measurement. Being different from current acoustic sensing systems for motion tracking, our technique evaluates the overall condition of the airway system and needs new methods to measure the received acoustic signal. As shown in Figure 1, narrowed airways produce extra signal reflections and can be measured from the signal's power spectrum. Similarly, we will measure the inflammation and mucus in airways as the signal's attenuation that indicates the airway's resistance against acoustic signal propagation.

Task 3: Big Data Analysis. When being widely used in public, the accuracy of our technique could be impaired by the individual difference of airway mechanics among humans. To properly identify and address such heterogeneity, we will recruit student volunteers at Pitt and instruct them to use our technique on a daily basis. The collected data will be analyzed using deep learning models such as LSTM and attention models (we will also design new deep learning methods to improve the performance), to develop generic models that depict the airway mechanics of big crowds. The outcome of this task will also provide important insights to better understand how changes of airway mechanics precede worsening of clinical symptoms in COVID-19.

Significant Results:

First, we have implemented the SpiroSonic design on commodity smartphones. To our best knowledge, SpiroSonic is the first spirometry system using commodity smartphones in regular home settings. It provides a convenient yet cost-free tool for continuous tracking and evaluation of pulmonary diseases, which are crucial to patients' wellbeing. It also contributes to early-stage diagnosis of COVID-19 out of clinic, and helps reduce the burden of public healthcare system in pandemic. The key characteristics of SpiroSonic are as follows: 1) SpiroSonic is accurate. Its error of measuring chest wall motion is constrained within 4mm. When being evaluated among healthy humans, its error of lung function monitoring is always lower than 3%. 2) SpiroSonic is adaptive. It can precisely remove the impact from various environmental and human factors, and allows flexible variations of smartphone's position (up to 20cm) and orientation (up to 30-degree tilting) during spirometry tests without impairing the accuracy. It also well adapts to humans' body conditions, as well as different types of clothes being worn. 3) SpiroSonic is lightweight. It is contactless and does not require any extra hardware. It consumes <15% of smartphone's battery life with 1-hour usage. 4) SpiroSonic is easy to use. It is implemented as an Android app, and its spirometry tests are fully automated and require the minimum involvement from users.
Furthermore, by collaborating with clinical pulmonologists and biostatisticians, we conducted a clinical study in the Children's Hospital of Pittsburgh of 4 months, over 83 pediatric patients that cover different ages, genders, body conditions and diseases. With the IRB approval, all studies were done in clinical rooms when patients visited the hospital for spirometry tests, and 281 data records from tests are collected. Results of our clinical study are as follows: 1) SpiroSonic's error of lung function monitoring is between 5% and 10% for most patients. Since the error of in-clinic spirometry is around 5%, results from SpiroSonic could be reliably used as clinical evidence. 2) We statistically demonstrate that patients' chest wall motion is strongly correlated to their lung function indices, and some of such correlations are linear. 3) SpiroSonic achieves high monitoring accuracy over different patient subgroups, divided by age, gender and disease. It is hence widely applicable to the large population of patients.

	Second, we have implemented our MyoMonitor system design as an Android smartphone app, which uses 20 kHz as the carrier wave of our encoded signal. Though commodity smartphones usually have two pairs of speaker and microphone for music playback or voice call, we choose top speaker along with bottom microphone because this combination can ensure the best results of channel estimation from our experiments. To minimize interaction needs, the subject only needs to signal the start and end of each test by pressing a phone volume button. The test protocol is suggested by clinicians based on a simple bicep workout and entire procedures are automated by voice and screen instructions. The protocol stipulates that the basic unit of our test is a group, in which we require the subject to complete as many biceps workouts as possible until he(she) feels hard to follow the speed of voice instructions. Each workout includes steps of preparation, lift-up, hold, lift-down and a resting interval for the following workouts. By explicitly defining the duration of these steps and the elevation that the dumbbell should be lifted, we make the protocol standardized so that people with different muscle condition should have similar feeling of fatigue after enough times of workout. By collaborating with orthopaedic doctors, we devised a protocol of monitoring biceps brachii fatigue. The protocol is instructed by a fully automated smartphone app with voice guidance. We conducted experiments over five student volunteers with more than 200 groups of workouts in total. 70% of the data can exhibit the expected results and consistency of fatigue evaluation. Our preliminary exploration of the technique paves the way for further clinical investigation and validation, which could be a potentially beneficial tool for patients with muscle myopathy and disorders.
Key outcomes or Other achievements:	During the past year, the research outcome of this project has resulted in one journal paper and one conference paper. The research work on developing and implementing SpiroSonic, a new mobile system that supports spirometry tests on commodity smartphones, has been accepted for publication by ACM MobiCom 2020, the best conference for mobile computing and networking. The research work on developing MyoMonitor that supports muscle fatigue evaluation on commodity smartphones has been accepted for publication at the Elsevier Smart Health Journal.

*** What opportunities for training and professional development has the project provided?**

One PhD student worked on the project, and the research results have been published at academic conferences and journals.

*** Have the results been disseminated to communities of interest? If so, please provide details.**

Our research work in this project has resulted in one journal paper and one conference paper. These publications will help people better understand our novel techniques that could make important contributions to combating the COVID-19 pandemic. We have also given seminar and summer camp talks to high school students to stimulate their interest in engineering majors.

*** What do you plan to do during the next reporting period to accomplish the goals?**

In the next reporting period, we plan to further expand our current work on acoustic mobile sensing, so that we could precisely explore and measure the internal characteristics of humans' airway lumens. To achieve this goal, new designs on acoustic signal waveforms and signal processing methods are needed. We also plan to resume our recruitment of student volunteers that has been delayed due to the pandemic and the university's suspension of human-related research and experimentation, to conduct experimentation of our developed systems on real human beings.

Products

Books

Book Chapters

Inventions

Journals or Juried Conference Papers
View all journal publications currently available in the NSF Public Access Repository for this award.

The results in the NSF Public Access Repository will include a comprehensive listing of all journal publications recorded to date that are associated with this award.

Song, Xingzhe and Yang, Boyuan and Yang, Ge and Chen, Ruirong and Forno, Erick and Chen, Wei and Gao, Wei. (2020). SpiroSonic: monitoring human lung function via acoustic sensing on commodity smartphones. *in Proceedings of the 26th International Conference on Mobile Computing and Networking (MobiCom)*. 1 to 14. Status = Deposited in NSF-PAR doi:https://doi.org/10.1145/3372224.3419209 ; Federal Government's License = Acknowledged. (Completed by Gao, null on 07/03/2021) Full text Citation details

Song, Xingzhe and Li, Hongshuai and Gao, Wei. (2021). MyoMonitor: Evaluating muscle fatigue with commodity smartphones. *Smart Health*. 19 (C) 100175. Status = Deposited in NSF-PAR doi:https://doi.org/10.1016/j.smhl.2020.100175 ; Federal Government's License = Acknowledged. (Completed by Gao, null on 07/03/2021) Full text Citation details

Licenses

Other Conference Presentations / Papers

Other Products

Other Publications

Patent Applications

Technologies or Techniques

Thesis/Dissertations

Websites or Other Internet Sites
Project website
http://www.pitt.edu/~weigao/reporting/covid.html

On this project website, we provide details regarding this specific project (personnel, papers, software, etc.).

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Gao, Wei	PD/PI	2
Chen, Wei	Co PD/PI	1
Forno, Erick	Co PD/PI	1
Huang, Heng	Co PD/PI	1
Song, Xingzhe	Graduate Student (research assistant)	3

Full details of individuals who have worked on the project:

Wei Gao
Email: weigao@pitt.edu

Most Senior Project Role: PD/PI
Nearest Person Month Worked: 2

Contribution to the Project: Lead the project.

Funding Support: This project

Change in active other support: No

International Collaboration: No
International Travel: No

Wei Chen
Email: wec47@pitt.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Lead the biostatistical analysis of data.

Funding Support: This project.

Change in active other support: No

International Collaboration: No
International Travel: No

Erick Forno
Email: erf30@pitt.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Providing clinical guidance of the project.

Funding Support: This project.

Change in active other support: No

International Collaboration: No
International Travel: No

Heng Huang
Email: heng.huang@pitt.edu
Most Senior Project Role: Co PD/PI
Nearest Person Month Worked: 1

Contribution to the Project: Be responsible for developing the AI algorithms for data analysis.

Funding Support: This project

Change in active other support: No

International Collaboration: No
International Travel: No

Xingzhe Song
Email: x.song@pitt.edu

Most Senior Project Role: Graduate Student (research assistant)
Nearest Person Month Worked: 3

Contribution to the Project: Designed and implemented the SpiroSonic and MyoMonitor systems.

Funding Support: This project.

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?
Nothing to report.

Were other collaborators or contacts involved? If so, please provide details.
Nothing to report

Impacts

What is the impact on the development of the principal discipline(s) of the project?

The COVID-19 pandemic is one of the biggest public health challenges in history. The fast spread of virus may quickly overload the public healthcare system, but is hard to evaluate out of clinic. The transformative nature of this research is to rethink how the commodity smartphones could be fully utilized for early-stage evaluation of COVID-19 infection at home, by turning various signal processing methods, sensing techniques and deep learning algorithms into actionable system development strategies. It has the potential to significantly alleviate the clinical burden of virus testing, and could contribute datasets that help better understand the virus' mechanics of affecting humans' airway systems.

Further, this proposed research, at a high level, follows two general principles: i) exploring the unique connection between COVID-19 infection and change of humans' airway mechanics, and ii) designing techniques that leverage the knowledge of such connection to measure unique indicators of COVID-19 infection in a contactless manner. Application of this general approach leads to the following intellectual merits: i) Technical advances in mobile acoustic sensing to evaluate the overall condition of humans' airway systems; ii) New acoustic waveform design that minimizes the signal distortion when being propagated in human airways; iii) New signal processing techniques to evaluate the humans' airway changes of mechanics due to COVID-19 infection; iv) Deep learning models that depict the generic characteristics of airway mechanics among big crowds; iv) Datasets collected from student volunteers that help better understand how changes of airway mechanics precede worsening of clinical symptoms in COVID-19.

What is the impact on other disciplines?

The outcomes of the proposed research could serve as a low-cost yet effective tool of COVID-19 infection testing in developing countries where healthcare facilities are not widely available. This proposed research, hence, has a direct and significant impact on the whole society. It can also be useful to produce datasets from COVID-19 patients, whom otherwise are hard to be accessed by healthcare workers due to the risk of infection. These datasets would be useful assets to many other disciplines such as biostatistics, bioinformatics and public health, for large-scale analysis and strategy planning.

What is the impact on the development of human resources?

Many of the research results have been integrated into the undergraduate curricula at the University of Pittsburgh, by adopting many perspectives of the research results for undergraduate students' course projects and senior design topics. The project has supported one PhD student working on their dissertation. The involvement of the graduate and undergraduate students into this research will prepare them for leadership roles in computer science research, academia, and industry.

What was the impact on teaching and educational experiences?
Nothing to report.

What is the impact on physical resources that form infrastructure?
Nothing to report.

What is the impact on institutional resources that form infrastructure?
Nothing to report.

What is the impact on information resources that form infrastructure?
Nothing to report.

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?
Nothing to report.

What percentage of the award's budget was spent in a foreign country?
Nothing to report.

Changes/Problems

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them

Due to the severe condition of COVID-19 pandemic, the University of Pittsburgh suspended all human-related research activities in the last months of 2020 and beginning months of 2021, and resumed these research activities in April 2021. This suspension significantly delayed our planned recruitment of student volunteers and system experimentation over these student volunteers in the Spring semester. In the upcoming year, we plan to recruit student volunteers in the Fall 2021 semester, and conduct experimentation on them accordingly. Data processing and analysis will then be conducted in the Spring 2022 semester.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects

See above.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Change in primary performance site location
Nothing to report.