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COVID-19 AND DIGITAL HEALTH: HOW INTELLIGENT SOLUTIONS ARE SHAPING HEALTHCARE FOR THE FUTURE

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BACKGROUND

The COVID-19 pandemic made several unprecedented realizations. One among them is the role of technology to fight crisis like the pandemic. While scientists in research labs are busy finding an effective vaccine, it is equally vital how governments worldwide are putting efforts to curb the pandemic.

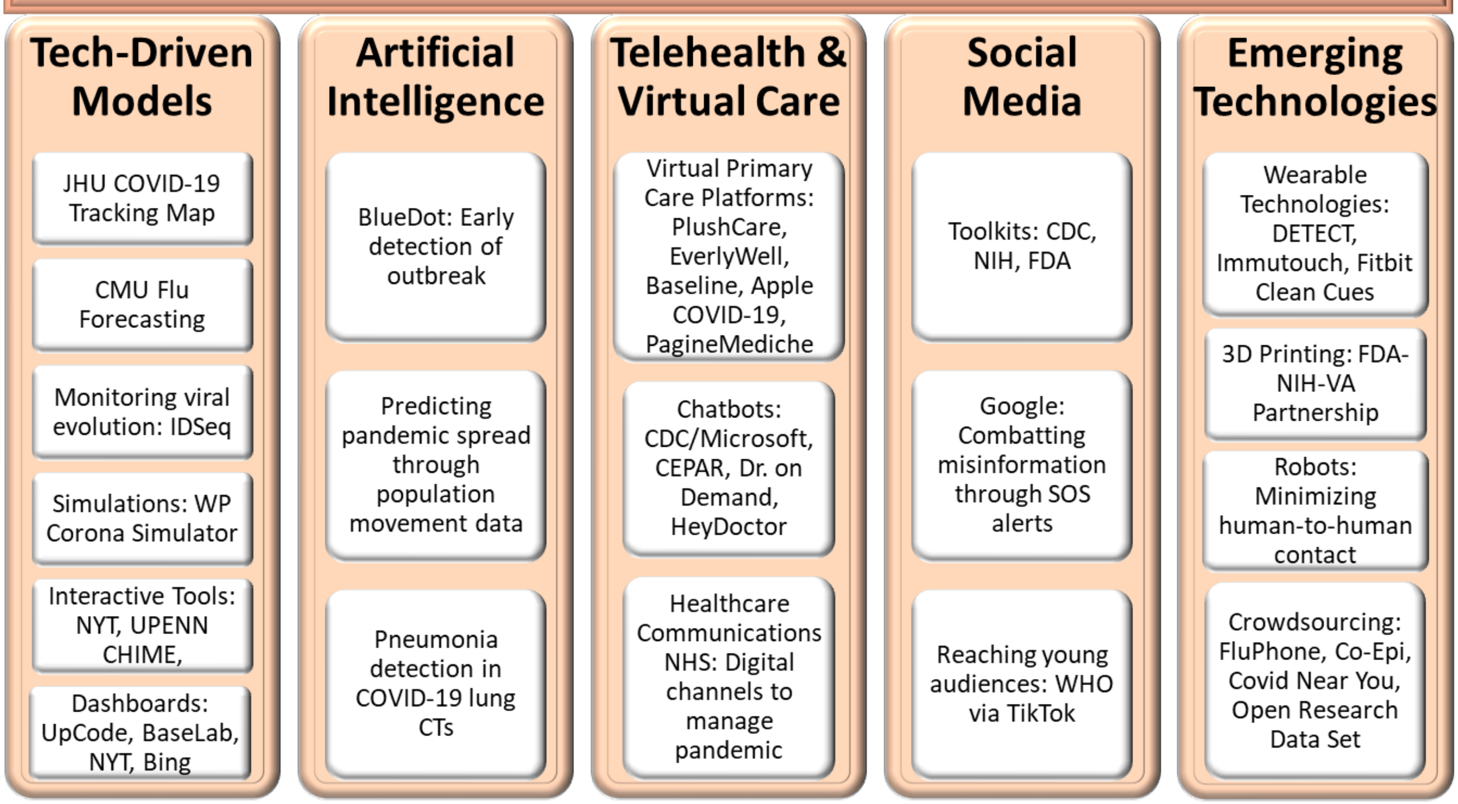
Health institutions are trying to gather, collate, analyze, and present information to the government to make meaningful and useful decisions to help in the pandemic. Technology plays an essential role in informing health systems and frontline health professionals to fight the crisis. Beyond that, the population under lockdown and adherence recommendations needs to be provided with information that helps mitigate concerns and make them ‘informed’ during the pandemic to take relevant actions. Our effort here is to summarize and highlight a few critical areas where ‘intelligent digital health’ has helped fight the pandemic. As shown in Figure 1, we draw insights for research and practice for the future through a brief synthesis reflecting on four themes: (1) technology-driven models, (2) artificial intelligence, (3) telehealth and virtual care, (4) the role of social media, (5) emerging technology such as wearables, and robots.

INTELLIGENT MODELS THAT INFORMED THE PUBLIC

Technology-driven models developed in response to COVID-19 have pioneered public outreach, provided real-time data, offered accurate forecasting, explained spread patterns, and predicted potential death tolls. With the epidemiological research they are based upon, these tools inform several aspects of the curve associated with COVID-19. Interactive maps and visualizations, emerging from the models, have emerged as essential tools to inform the public about COVID-19.

The understanding provided by the technology-driven models broadened the scope of response by the public and governments to the pandemic. Subsequent efforts to deploy resources and capabilities crucial to flatten the curve have helped in several instances. Similar models have helped administrators to project hospital capacity and personal protection equipment (PPE) supply requirements. However, concerns also remain to what extend these models and subsequent information has been helpful; unless they were filtered and presented in a meaningful way. While visualization tools with granular-aggregate-parsing mechanisms were helpful, the efficacy of these maps and

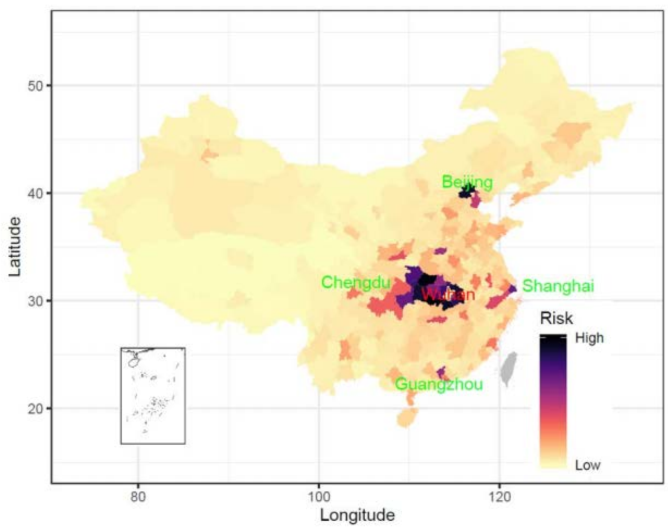
FIGURE1: SCOPE OF INTELLIGENT HEALTH FIGHTING THE COVID-19 PANDEMIC



visualization on the public remains a broader discussion and research topic. A brief description of several of these models, maps, and visualizations follows.

JHU COVID-19 Tracking Map: The JHU COVID-19 Tracking Map tracks total cases and deaths by state and county and positivity rates and rolling 7-day averages[1]. It has become the central dashboard for monitoring the spread of COVID-19 in the United States in almost real-time. The map allows authorities to rely on real-time data collection, track and publicize the numbers for disease reporting, and provide statistics for analysis. As the COVID-19 outbreak became global in scope, the team at JHU expanded the project to explain and contextualize the spread of the virus, presenting critical trends and publishing daily snapshots of the progression of the pandemic every 24 hours. This map motivated several other projects.

FIGURE 2: RISK OF CITIES IN MAINLAND CHINA RECEIVING TRAVELERS WITH 2019- NCOV INFECTIONS FROM WUHAN DURING THE LUNAR NEW YEAR MIGRATION. (IMAGE CREDIT: LAI SHENGJIE, UNIVERSITY OF SOUTHAMPTON)



Forecasting Technology: A team from Carnegie Mellon University has adapted its flu forecasting technologies to predict coronavirus spread[2]. These technologies rely on a nowcast (an estimation of how many people are currently infected), machine algorithms that explore historical flu data and flu-related web traffic, and crowdsourced aggregate predictions. Similarly, IDseq is an open-source, online service that detects and monitors metagenomic pathogens through metagenomic next-generation sequencing (mNGS)[3]. The IDseq portal accepts raw mNGS data, then reports and visualizes taxonomic relative abundances and other information critical for data interpretation. Unlike other mNGS data analysis tools, IDseq does not require access to server-class hardware resources. This minimizes barriers to entry for scientists in resource-poor environments. Given the novelty of COVID-19, it is too early to tell whether these models can predict the viral outbreak and evolution accurately, but experts believe they have promise going forward.

Simulation Technology: Washington Post's Corona simulator describes spread patterns by providing animated simulations with a dot representing each person[4]. Whenever a brown dot (representing someone infected) comes into contact with a blue dot (representing a healthy person), the blue dot turns brown and goes on to infect other blue dots before turning purple (representing a recovered person). This baseline simulation gave rise to more complex simulations and graphs. These explored real-life parameters such as forced quarantine, attempted quarantine, moderate distancing, and extensive distancing.

Interactive and Educational Tools: The New York Times developed an interactive tool to contextualize COVID-19 by comparing it with other leading causes of death in the United States[5]. This tool features two sliders. One allows a user to choose an infection rate, and the other allows a user to choose a fatality rate. The algorithm then determines the death toll based on these values. This comparative tool is useful to consider the burden of COVID-19 on the American health system.

Researchers at JHU and Harvard developed an educational tool to juxtapose the spread of COVID-19 and healthcare system capacity[6].This simulator allows a user to input values such as population size and the initial number of infected patients and clinical parameters such as incubation duration, duration of infections, and more. The simulation also allows a user to set transmission rates, seasonality, asymptomatic infections, and pre-symptomatic transmission. The University of Pennsylvania developed a tool known as

[1] Dong, E., *Hongru Du and Lauren Gardner. 2020.* An Interactive Web-Based Dashboard to Track COVID-19 in Real Time: p. 30120-1.
[2] Spice, B. *Carnegie Mellon Extends Forecasting of Flu-Like Illness.* 2020; https://www.cs.cmu.edu/news/carnegie-mellon-extends-forecasting-flu-illness.
[3] Kalantar, K.L., et al., *IDseq—an open source cloud-based pipeline and analysis service for metagenomic pathogen detection and monitoring.* GigaScience, 2020. **9**(10): p. giaa111.
[4] Stevens, H. *Why outbreaks like coronavirus spread exponentially, and how to "flatten the curve".* 2020. https://www.washingtonpost.com/graphics/2020/world/ corona-simulator/.
[5] Josh Katz, M.S.-K., Kevin Quealy. *Could Coronavirus Cause as Many Deaths as Cancer in the U.S.? Putting Estimates in Context.* The New York Times 2020. https://www.nytimes.com/interactive/2020/03/16/upshot/coronavirus-best-worst-death-toll-scenario.html
[6] Hill, A. *Modeling COVID-19 Spread vs. Healthcare Capacity.* 2020. https://alhill.shinyapps.io/COVID19seir/.

the COVID-19 Hospital Impact Model for Epidemics or CHIME[7]. This computes the theoretical number of people infected with COVID-19 in a closed population over time. It applies to the period before a region's peak number of cases and accounts for social distancing. It provides the projected number of daily COVID-19 admissions, the projected census of COVID-19 patients, a hospital's PPE requirements, and a hospital catchment region's population for suspected infected and recovered patients. These tools allow administrators and policymakers to be better prepared to address the challenges of COVID-19.

Dashboards: There exist several noteworthy dashboards beyond the JHU COVID-19 Tracking Map. One is UpCode, which relies on data from the Singapore Ministry of Health, providing essential insights into the coronavirus outbreak in Singapore. It graphs the rise and fall of active, reported, critical, and recovered cases. The BaseLab, another dashboard, includes a global map, daily and cumulative case counts for each country, and notes which countries have shown the most massive increase and largest percentage increase in cases.

New York Times also developed dashboards that offer a look at the effect of COVID-19 on every continent through various maps and graphs. It tracks increasing, decreasing, and reversing prevalence trends. Bing also provides a specific dashboard to the United States, tracking active, recovered, and fatal cases in each state. Unlike other dashboards, it provides information on over 198 leading vaccine candidates[8].

ARTIFICIAL INTELLIGENCE SOLUTIONS

A Canadian health monitoring company called BlueDot provided several early warnings of the COVID-19 outbreak. BlueDot uses an AI-based algorithm to explore and explain the spread of infectious diseases by monitoring foreign language news reports, animal and plant disease networks, and official proclamations[9]. BlueDot predicted the outbreak earlier than the CDC and the WHO, proving that AI may outpace traditional intergovernmental communication. The algorithm correctly anticipated the spread of COVID-19 from Wuhan to Bangkok, Seoul, Taipei, and Tokyo by tracking global airline data. BlueDot's two-step approach — automated data sifting, followed by a human interpretation by a team of epidemiologists — has proven to be accurate.

Following BlueDot's prediction success, a team of scientists, including the CEO of BlueDot, responded to the potential exacerbation of increased travel for the Lunar New year Festival. The team performed preliminary risk analyses regarding the viral spread within and beyond China by aggregating historical population movement data. The team presented these data in various graphs, charts, and maps, which provided accessible information to those implementing public health interventions.

Exploratory and predictive models were also used, such as an AI model showing how shutdowns delayed the epidemic growth. Chinese officials attempted various non-pharmaceutical interventions to slow the spread of the virus in January 2020. Suspected and confirmed cases were isolated, public transport was suspended, schools and entertainment venues were closed, and public gatherings were banned. Despite this high-level response, COVID-19 cases rose in and outside of China. Given this, an international coalition of scientists attempted to determine the impact of travel restrictions and transmission control measures[10]. The study concluded that these measures minimize the spread and scope of the epidemic, despite challenges such as extensive public transportation networks and increased travel for the Lunar New Year Festival. This conclusion is notable because it provides a quantitative basis for continuing public health measures around the world.

AI may also be used in the diagnostic process. Hospitals in China currently use AI software to detect signs of COVID-related pneumonia in lung CT scans[11]. The software was reconstructed using pneumonia detection algorithms to look specifically for pneumonia associated with COVID-19. These technologies can detect coronavirus in CT scans of patients' chests with 96% accuracy against viral pneumonia cases, and specific software only takes 20 seconds to determine whether a CT scan showed COVID-19 pneumonia. This is compared to the average time of 15 minutes for a radiologist to decide. The software is also helpful because diagnosing COVID-19 from a lung scan, while not definitive, is much faster than waiting for a SARS-CoV-2 test result from an overburdened laboratory. The time-saving benefits of diagnosing COVID-19 with the help of AI may pertain to overall hospital efficiency, especially in hospitals that experience bottlenecks and radiology.

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[7] Michael Becker, C.C. *Announcing CHIME, A tool for COVID-19 capacity planning.* Speaker Series 2020. http://predictivehealthcare.pennmedicine.org/ 2020/03/14/accouncing-chime.html.

[8] Patel, N.V. *The best, and the worst, of the coronavirus dashboards.* Tech and health 2020. https://www.technologyreview.com/2020/03/06/905436/best-worst-coronavirus-dashboards/.

[9] Niiler, E. *An AI Epidemiologist Sent the First Warnings of the Wuhan Virus.* Science 2020. https://www.wired.com/story/ai-epidemiologist-wuhan-public-health-warnings/.

[10] Lai, S., et al., *Preliminary risk analysis of 2019 novel coronavirus spread within and beyond China*. 2020.

[11] Greene, T. *Alibaba's New AI System Can Detect Coronavirus in Seconds*. 2020. https://thenextweb.com/neural/2020/03/02/alibabas-new-ai-system-can-detect-coronavirus-in-seconds-with-96-accuracy/.

Based on these examples, the lesson of COVID-19 should encourage all health systems to develop and deploy artificial intelligence-based solutions. Using these tools, we may be able to identify indicators that would have otherwise gone unnoticed and ultimately contribute and strengthen the National Syndromic Surveillance Program of the CDC[12].

TELEHEALTH AND VIRTUAL CARE SOLUTIONS

Over the past few months, the healthcare industry has seen an exponential increase in the use of telehealth and virtual care models. Demands for relevant telehealth services, such as virtual visits and chatbots, have skyrocketed[13]. As such, the most successful health systems will work to leverage this seismic change fully. Over the last few months, we have seen a shift in moving the care model from hospitals and clinics to home health-based care. Beyond this, health systems are trying to automate their customer-patient response by providing solutions and guiding patients to proper care through chatbots. Several of these innovations are described below.

PlushCare is a virtual primary care platform that offers COVID-19 guidance and testing services. They launched a coronavirus quiz that contains simple yes-or-no questions, then provides quiz-takers with a risk assessment and actionable recommendations[14]. They also deployed an at-home viral testing system. The patient takes a sample, returns a testing kit to a partner lab, and awaits results, which only take 24 hours. EverlyWell, another virtual care service, developed a similar at-home testing system, as did Baseline COVID-19, a collaboration by the State of California, Rite Aid, and Google. This system guides individuals concerned they have been exposed to COVID-19 through screening, testing, and delivery of results. The screening questions are designed to help public health authorities prioritize individuals for testing, which differentiates it from the systems provided by PlushCare and EverlyWell. Apple, meanwhile, developed a COVID-19 screening tool that works much like those described above; however, this tool has been repurposed into an app called Apple COVID-19, which improves user accessibility.

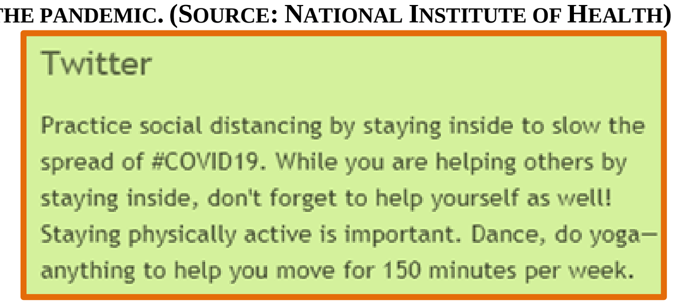
PagineMediche is an Italian virtual care platform connecting patients with online health professionals for COVID-19 evaluation and monitoring. The platform launched a symptom guide and corresponding chatbot to provide virtual evaluation and recommendations. Other companies followed this approach to reduce hospital visits and cross-contamination. The CDC partnered with Microsoft to launch a testing chatbot. The Office of Critical Event Preparedness and Response and Emory University School of Medicine provided a similar chatbot, as did Dr. on Demand, HeyDoctor, and more virtual care platforms.

Meanwhile, Healthcare Communications, the UK-based patient communication partner of the NHS, has initiated digital channels to manage COVID-19. These channels include a COVID-19 chatbot assistant, instant patient messaging, eClinic video consultations, and simple doctor-patient virtual interfaces. They have also moved patient forms online and provided a digital mailing service for patient groups that require immediate guidance. These services are optimized for use by any NHS organization and do not charge any licensing fees [15].

SOCIAL MEDIA

The CDC, NIH, and FDA all provide social media toolkits with sample posts, accessible to the public and health authorities. These equip users with sample messages for Facebook, Instagram, and Twitter about masks, social distancing, hand washing, action items for those who are ill, stopping the spread, contract tracing, and more. They also provide shareable insights on Emergency Use Authorizations, adverse treatment effects, vaccines, online fraud, testing, poison hotlines for people who have ingested treatments that were not approved by the FDA, grocery shopping guidelines, blood donation, and more. Some of these toolkits delve into behavioral health steps as well.

FIGURE 3: A SAMPLE TWITTER MESSAGE PROVIDED BY THE NIH TO ENCOURAGE HEALTHY PRACTICES LIKE EXERCISE DURING THE PANDEMIC. (SOURCE: NATIONAL INSTITUTE OF HEALTH)



While these toolkits prove that social media has been used responsibly and effectively amid the pandemic, there is an ongoing social media infodemic of misinformation. With more people spending time online due to the pandemic, the omnipresence of misinformation is a cause for concern.

[12] https://www.cdc.gov/nssp/index.html
[13] Khalid, A. *Telemedicine Faces Unprecedented Demand in the Wake of Coronavirus*. Big Tech 2020. https://qz.com/1821549/telemedicine-faces-unprecedented-demand-in-the-wake-of-coronavirus/.
[14] Khalid, A. *Telemedicine Faces Unprecedented Demand in the Wake of Coronavirus*. Big Tech 2020. https://qz.com/1821549/telemedicine-faces-unprecedented-demand-in-the-wake-of-coronavirus/.
[15] *COVID-19 Update: Moving to Digital Channels to Manage Demand*. 2020. https://healthcare-communications.com/2360-2/.

Technology experts believe social media platforms must design channels for accurate information to reach users while limiting the unrestricted spread of dangerous misinformation among users. Google has worked to combat misinformation in its search results [16]. Google searches related to the virus now trigger an SOS alert so that results are presented according to public health importance rather than according to keywords' frequency and location[17]. Google now displays trusted, mainstream publications such as the CDC and the WHO as search outcomes for COVID-19 relevant information. Google has also removed videos that make erroneous claims about the virus and medical treatments. Facebook, Twitter, and Pinterest have taken similar steps. The WHO, meanwhile, has reached a crucial audience with an unexpected approach. The UN's health agency joined TikTok, a video-sharing social networking service popular with teenagers and young adults[18]. Here, the WHO shares short videos to communicate vital COVID-19 information to a young, global audience.

Emerging Technologies: 3D Printing, Wearables, and Robots

3D Printing: The FDA is working in partnership with the NIH and the VA to support non-traditional manufacturing through a 3D-printing exchange. Items provided via 3D printing include PPE such as face shields, respirators, ventilator values, mask connectors for CPAP and BiPAP, PEEP masks, personal accessories, bio-models, and much more[19][20]. The FDA, IH, and VA partnership has passed community-submitted designs for clinical approval and has matched 500,000 face shields and 348,000 face masks with healthcare providers. Other similar efforts have been successful in manufacturing and distributing essential PPE during the pandemic. However, many experts warn that 3D printing of these products is a stopgap because large-scale 3D-printing is relatively inefficient when it comes to time and cost. Beyond this, the FDA states that 3D printed PPE may not provide the same air filtration level or protection against infected fluids as the FDA approved counterparts [21].

Wearable technologies have been developed in response to COVID-19. DETECT, which stands for Digital Engagement and Tracking for Early Control and Treatment, measures, and anonymously reports resting heart rates to monitor and predict potential viral outbreaks [22]. The team at DETECT hopes this technology will give public health officials early warning about viral outbreaks and assist the average user in monitoring their health[23]. Immutouch is a smart band designed to protect users from germs and break bad habits. The smart band vibrates each time a user touches their face; over time, this reminder shapes a user's behavior and cultivates cleaner habits. Moreover, Fitbit now provides Clean Cues, which remind a user to wash their hands once every hour, limiting the spread of respiratory illnesses such as COVID-19.

Figure 4: A care home resident in Belgium interacts with a social robot. (Source: Yves Herman, Reuters)

Robots: At the start of the pandemic in China, several tech companies introduced robots to minimize or eliminate human-to-human contact. One company introduced robots to bring takeout from kitchens to delivery workers and customers. This reduced the number of contacts while

[16] Newton, C. *Google has been unusually proactive in fighting COVID-19 misinformation*. Policy 2020. https://www.theverge.com/interface/ 2020/3/11/21173135/google-coronavirus-misinformation-youtube-covid-19-twitter-manipulated-media-biden.
[17] Donovan, J. *Here's how social media can combat the coronavirus 'infodemic'*. Tech and health 2020. https://www.technologyreview.com/2020/03/17/905279/ facebook-twitter-social-media-infodemic-misinformation/.
[18] Basu, T. *The WHO got on TikTok to teach teens about coronavirus*. Humans and technology 2020. https://www.technologyreview.com/2020/03/02/905588/the-who-got-on-tiktok-to-teach-teens-about-coronavirus/.
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[22] https://clinicaltrials.gov/ct2/show/NCT04336020
[23] Radin, J.M., et al., *Harnessing wearable device data to improve state-level real-time surveillance of influenza-like illness in the USA: a population-based study*. The Lancet Digital Health, 2020. **2**(2): p. e85-e93.

picking up food and incentivized customers to stay out of grocery stores[24]. Other companies pioneered self-driving robots to bring various goods to medical workers in Wuhan and sent dozens of bots into Wuhan hospitals to disinfect isolation wards, ICUs, and ORs. Robots have also been used in a clinical capacity. These robots are equipped with stethoscopes and can take a patient's vitals, then communicate the patient's status to physicians and other medical personnel through a large screen. Clinical robots have also been repurposed to measure patients' fevers. These robots have reduced the risk of infection and allowed doctors to speak with coronavirus patients via video chat [25].

Meanwhile, one robotics company specializing in humanoids, social robots, and personal assistants has deployed robots to care homes in Belgium [26]. These robots are equipped with communication, recognition, and navigation technologies. Their use in care homes is focused on social connection, mainly through Facebook messenger video calls.

Crowdsourcing: Several tools that rely on crowdsourcing have been developed in response to the pandemic[27]. These include crowd mapping techniques used by China and South Korea, FluPhone (a disease-tracking app), Co-Epi (a GitHub project that uses smartphone and cloud computing technology to minimize infection risks), and Covid Near You, which allows the public to report COVID-19 symptoms, thereby providing a local and national crowd map of infection.

Crowdsourcing technologies have also helped develop open-source, machine-readable data sets, such as the Open Research Data Set. Crowdsourcing has also proven valuable in developing disease-specific registries and cohort studies that study the interaction of COVID-19 and existing diseases, such as cancer and hepatitis. Finally, crowdsourcing has assisted in AI-based protein prediction, which may be useful to vaccine development, and has helped scientists to determine the extent to which the public is social distancing.

One unique application of crowdsourcing allows COVID-19 researchers to take over people's unused computational resources to generate data that can be used by laboratories around the world as an open science collaboration[28]. Another application allows innovators to reach out to the public for ideas and solutions to support COVID-19 patients and those in quarantine. This encourages the participation of students, innovators, startups, communities, NGOs, and more.

Conclusion: The challenges presented by the COVID-19 pandemic have offered an unprecedented opportunity for the expansion and acceleration of intelligent digital health technologies, including forecasting, simulations, models, and dashboards. In the face of COVID-19, innovative AI technologies have proven indispensable, as has telehealth and virtual care solutions. Other technologies, such as wearables, 3D printing, robots, and crowdsourcing, are at the forefront of the pandemic response. Not only have the technologies described in this brief combated the pandemic – they have emerged as the future of intelligent healthcare.

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