Postprint: Analysis of Big Data and Artificial Intelligence Applications in COVID-19 Prevention and Control from the Haddon Model Perspective

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Abstract

Big data and artificial intelligence technologies have demonstrated significant potential in the prevention and control of coronavirus disease 2019 (COVID-19); however, scant research has comprehensively investigated their application status and future trends. This study departs from an analysis of the challenges confronting COVID-19 prevention and control, and following an exposition of the advantages of big data and artificial intelligence technologies, presents a systematic overview of commonly employed technologies and their practical application cases throughout the pandemic response. Subsequently, through the lens of the Haddon model, and focusing on the three core elements of infectious disease—source of infection, transmission route, and susceptible population—this research undertakes an in-depth exploration of big data and artificial intelligence applications across three stages: pre-epidemic, epidemic, and post-epidemic. The findings hold significant implications for elucidating the positive roles and developmental trajectories of these technologies at various pandemic stages, enhancing the efficiency and quality of prevention and control measures, and effectively addressing future emerging infectious diseases.

Full Text

Analysis of the Applications of Big Data and Artificial Intelligence in the Prevention and Control of COVID-19 from the Perspective of Haddon Model

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Abstract

Big data and artificial intelligence technologies have played a positive role in the prevention and control of COVID-19 outbreaks. However, their application and future trends have not been comprehensively discussed. Starting from the problems faced in the prevention and control of COVID-19, this study provides an overview of the common big data and artificial intelligence technologies and their practical application cases. Based on the Haddon model perspective, we discuss the application of these technologies focusing on three elements—infectious source, route of transmission, and susceptible population—across three stages: before, during, and after the COVID-19 outbreak. The results are important for clarifying the positive role of big data and artificial intelligence at each epidemic stage, identifying directions for development and application, improving the efficiency and quality of COVID-19 prevention and control, and effectively responding to new infectious diseases in the future.

Keywords: COVID-19; Haddon model; Big data; Artificial intelligence; Prevention and control of epidemics; Application

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1 Information Retrieval Strategy

We conducted a literature search using electronic databases including PubMed, CNKI (China National Knowledge Infrastructure), and Wanfang Data for Chinese and English papers published between January 1, 2019, and May 1, 2023. Search terms included: (1) "COVID-19" or "novel coronavirus" ; (2) "big data" ; (3) "artificial intelligence" ; (4) "prevention" ; (5) "control" ; and (6) "application." Search combinations included "(1)+(2)" , "(1)+(3)" , "(1)+(4)+(5)" , or "(1)+(2)+(3)+(6)" according to specific database requirements. Additionally, we reviewed WHO special reports, health commission websites, government reports, corporate product technical promotions, and academic conference reports. Inclusion criteria were: (1) involvement of big data or AI technology; (2) targeting COVID-19; (3) inclusion of prevention or control measures; and (4) specific technology applications in epidemic prevention and control. Exclusion criteria were: (1) technologies outside big data or AI; (2) focusing on infectious diseases other than COVID-19; and (3) theoretical or implementation process descriptions. Based on included literature, we summarized relevant evidence and information.

2 Problems in COVID-19 Prevention and Control

The COVID-19 prevention and control process faces numerous problems and challenges. First, epidemic prevention involves multiple stages including monitoring, early warning, response, task dispatch, and execution. Traditional reliance on manual staffing and operation at each checkpoint creates heavy workloads and low efficiency, making it difficult to meet the urgent timeliness demands of epidemic control. Second, the massive multimodal data generated by epidemic control overwhelms the capacity of existing technologies for information reading and integrated processing. Third, in scenarios such as epidemiological investigation, disinfection, and public education, traditional manual approaches not only increase workload and reduce efficiency but also heighten exposure and cross-infection risks for healthy populations and healthcare workers, undermining epidemic control efforts. Additionally, epidemic control generates substantial health and medical data whose information value cannot be effectively extracted using traditional statistical analysis methods. Finally, epidemic control involves large amounts of privacy-sensitive information distributed across various levels of response activities, and existing information security technologies cannot provide adequate protection.

3 Advantages of Big Data and AI Technologies

Given these challenges, big data and AI technologies have been widely applied due to several key advantages. First, they reduce manual burden and improve work efficiency by developing and deploying intelligent robots to partially replace humans in critical epidemic control processes, accelerating the flow and operation of anti-epidemic tasks. Second, they offer efficient capabilities for reading, storing, and processing massive information, improving the input, recognition, and analysis of multimodal epidemic data and enhancing data processing and decision-support efficiency [3-4]. Third, they replace humans in numerous epidemic control tasks—for example, using intelligent robots for epidemiological investigation, disinfection, and delivery to avoid exposing key populations to infection sources or cross-infection [5]. Fourth, they enable deep mining and utilization of massive epidemic data to support decision-making, allowing more effective use of epidemic data for COVID-19 prevention and control [6-7]. Finally, they provide reliable data security and privacy protection, with specialized technical measures to prevent information leakage as a prerequisite for application in epidemic control.

4 Commonly Used Big Data and AI Technologies in Epidemic Prevention and Control

Currently, commonly used big data and AI technologies in COVID-19 prevention and control include machine learning, robotic process automation, AI-powered optical character recognition (OCR), natural language processing, intelligent voice robots, intelligent interaction, computer vision, knowledge graphs, and privacy computing (Table 1).

4.1 Machine Learning

Machine learning is an interdisciplinary field focused on data-driven learning that enables computers to identify patterns from complex data and statistical information. By simulating or implementing human learning behaviors, it acquires new knowledge or skills to predict future outcomes or trends, reorganizes existing knowledge structures, and continuously optimizes algorithms and performance. In epidemic control, machine learning analyzes multimodal epidemic big data to enable early monitoring and warning of epidemic trends, timely protection of susceptible populations, and improved utilization efficiency and quality of epidemic data. An Iranian study used multiple machine learning algorithms to mine health data from 1,500 COVID-19 patients, finding that the random forest algorithm achieved superior predictive performance with accuracy, sensitivity, and specificity of 95.03%, 90.70%, and 95.10%, respectively—important for identifying mortality risk and enabling early intervention [8].

4.2 Robotic Process Automation

Robotic process automation is a business process automation technology based on software robots and AI that automates and intelligently handles desktop-based business workflows meeting specific applicability requirements. These tasks are typically numerous, repetitive, and definable through strict rules and outcomes. By developing and deploying process robots in key stages—pre-epidemic monitoring and warning, mid-epidemic control and treatment, and post-epidemic resumption of work and production—epidemic control tasks can flow efficiently across institutions and personnel, reducing manual staffing and operations and enabling automated, intelligent operation across the entire epidemic control chain to ensure timely decision-making, dispatch, and execution. A Chinese study showed that applying robotic process automation to school financial systems during COVID-19 cost only one-third of a full-time employee' s salary while completing the workload of 2–5 full-time staff through 24/7 operation, reducing COVID-19 exposure and transmission while solving financial operations problems [9].

4.3 AI-Powered OCR

OCR technology reads information from images and videos and converts it into editable, searchable digital formats. Combining hardware and software, OCR uses hardware to scan documents, detects dark and light patterns to identify shapes, then translates these shapes into computer code for processing using character recognition software. While OCR enables automated data reading, its accuracy, speed, and usability remain limited. Integrating OCR with AI improves recognition efficiency and accuracy, enabling intelligent reading of massive datasets. For example, one study used OCR technology with regular expressions to automatically verify health codes, travel codes, and nucleic acid test screenshots, combined with integrated facial recognition gates at smart construction sites, achieving automated, unmanned, and intelligent personnel entry management at construction sites during epidemic control [10].

4.4 Natural Language Processing

Natural language processing enables effective communication between humans and computers using natural language. Based on big data, machine learning, and speech recognition, it enables deep question-answering, machine translation, and human-computer dialogue for practical applications. In epidemic control, natural language processing allows computers to read and understand human language, and combined with speech recognition, enables electronic, automated, and intelligent natural language communication in epidemic control work—improving interaction efficiency, reducing manual workload, and enabling timely adjustment of prevention policies through analysis of COVID-19-related public opinion trends. A U.S. study using natural language processing to analyze patient data from COVID-19 assessments and treatments achieved ideal results (recall 85.8%, accuracy 81.5%), successfully enabling data-driven predictive analytics and patient advising during the pandemic [11].

4.5 Intelligent Voice Interaction Systems

Intelligent voice interaction systems, also known as intelligent voice robots, analyze user inquiries and responses to system questions through natural language processing and speech recognition, then dynamically provide targeted answers to enable interactive, intelligent human-computer question-answering scenarios. These systems have been widely applied in COVID-19 prevention and control—for example, one study developed an intelligent voice interaction system based on natural language processing technology for telephone-based epidemiological investigation, patient screening and triage, intelligent Q&A hotlines, voice broadcasting, and science education, partially replacing manual labor and providing uninterrupted 24/7 epidemic control services [5,12].

4.6 Computer Vision

Computer vision identifies, extracts, and understands information features from videos and images through machines, involving computer hardware and software, image processing, natural language processing, optical imaging, and sensors. It replaces human eyes to complete measurement, recognition, and judgment tasks, improving business flexibility and automation. Epidemic control involves massive video and image data that traditional manual verification cannot handle. Computer vision technology automatically identifies epidemic-related video and image data, combined with necessary manual verification, to effectively improve information extraction, data parsing, and decision-support efficiency in applications such as travel code verification, population screening, activity trajectory analysis, facial recognition, and medical imaging-assisted diagnosis [2,6,13]. For example, LI et al. [14] proposed a computer-aided diagnostic model that identifies COVID-19 from chest X-rays using machine vision, achieving accuracies of 0.9966 and 0.9901 on two public COVID-19 imaging databases, providing radiologists with reliable practical references.

4.7 Knowledge Graphs and Graph Computing

Knowledge graphs combine graphics, informatics, applied mathematics, visualization technology, and bibliometric citation analysis to visually display target core knowledge structures and relationship networks in graphical form. Graph computing models data as graphs to obtain results unavailable from flat perspectives. For massive data, knowledge graphs and graph computing transform existing information storage and management patterns, graphically revealing complex relationships to improve information query and analysis efficiency in complex scenarios. For example, analyzing multi-source heterogeneous epidemic data through knowledge learning and structural analysis, establishing large-scale knowledge graph entities and relationships can reveal complex relationships among the three epidemic transmission elements, trace transmission chains, predict development trends, simulate "decision-effectiveness" models, and integrate multi-dimensional information to support epidemic control decisions [15-16].

4.8 Other Technologies

Other commonly used big data and AI technologies in epidemic control include intelligent interaction and privacy computing. Intelligent interaction refers to front-end devices applied in multiple scenarios, including intelligent disinfection robots, sampling robots, investigation robots, and self-service verification channels, enabling contactless, 24/7 prevention and control measures targeting infectious sources, transmission routes, and susceptible populations in epidemic-related locations. Privacy computing comprises technologies that process and analyze data without revealing original data to data owners, making data "usable but invisible" during circulation and utilization. Since epidemic control involves large amounts of sensitive health information, privacy computing enables secure cross-institutional and cross-regional fusion and privacy protection of multimodal epidemic data, promoting deep mining and decision-support applications of epidemic big data.

5 Application of Big Data and AI Technologies at Various Stages of COVID-19

The use of big data and AI technologies runs through all stages of COVID-19 emergence and spread. Compared with other public health events, COVID-19 features rapid transmission, large numbers of infections, broad departmental involvement, massive data, and tight response timelines, posing new requirements and challenges for big data and AI applications—including the need to process massive multimodal data, apply different technical methods at different epidemic stages, emphasize contactless information collection, analysis, decision-making, and action, and prioritize temporal and spatial information [17-19]. In injury epidemiology, Haddon proposed a classic injury prevention and control model that addresses three conditions (agent, host, and environment) across three stages: pre-event, event, and post-event [20]. Following the Haddon injury prevention model, this study divides the COVID-19 epidemic into pre-epidemic, mid-epidemic, and post-epidemic stages, then examines application scenarios of big data and AI at each stage (Figure 1 [Figure 1: see original paper]) and prevention/control measures targeting the three elements—infectious source, transmission route, and susceptible population (Table 2).

5.1 Pre-Epidemic Stage

Infectious Source: Before COVID-19 emergence, machine learning algorithms analyze public internet search and medical consultation records for early detection and warning, while intelligent voice interaction systems enable early patient screening and triage [5,21].

Transmission Route: Intelligent disinfection robots perform routine contactless disinfection of potential transmission media and venues, while intelligent robots conduct contactless environmental sampling and testing to promptly identify and block transmission routes [22-23].

Susceptible Population: Intelligent voice robots conduct routine science education and public awareness campaigns on COVID-19 prevention, increasing public knowledge, skills, and awareness. Intelligent voice interaction systems provide epidemic-related information consultation and psychological counseling to alleviate public anxiety and panic [5,12]. Additionally, technologies including intelligent voice, computer vision, AI OCR, and intelligent robots automate and accelerate routine operations and intelligent approval in pre-epidemic scenarios such as viral antigen and nucleic acid testing, electronic health codes and travel credentials, and target population screening, ensuring efficient formulation, distribution, allocation, and execution of epidemic control measures while reducing labor and time costs (Figure 1) [2,22-24].

5.2 Mid-Epidemic Stage

Infectious Source: During the epidemic, AI-powered OCR rapidly detects and reads massive epidemic data including travel records, health status, and nucleic acid test results, enabling second-level entry and verification of tens of thousands of data items to support timely decision-making for personnel screening, containment zone designation, and other measures, effectively shortening response times [19,25]. Natural language processing extracts and analyzes epidemic-related natural language data from investigation calls, customer service hotlines, and intelligent robot Q&A to identify public spatiotemporal information, concerns, and demands, enabling overall public opinion monitoring and preliminary high-risk population screening [5,11]. Multimodal big data mining precisely traces infectious sources to quickly clarify transmission chains and implement targeted measures. Intelligent robots perform ward rounds, consultations, medication delivery, and meal distribution to prevent healthy populations from contacting infectious sources.

Transmission Route: Knowledge graphs and graph computing enable rapid scenario analysis to assess regional and venue risk levels and implement corresponding control measures. Intelligent robots conduct contactless on-demand disinfection of potential transmission routes and contactless material delivery.

Susceptible Population: Computer vision assists manual verification of nucleic acid tests, health codes, travel credentials, and close contact/activity trajectory information, while AI speech recognition improves investigation efficiency [22,26]. Computer vision and big data technology also assist physicians in rapid, accurate lung CT diagnosis for patients, reducing healthcare workload while enabling early intervention and treatment [2,6].

5.3 Post-Epidemic Stage

Infectious Source: Post-epidemic, intelligent robots perform contactless terminal disinfection and sampling to ensure complete recovery of infectious sources.

Transmission Route: Intelligent robots conduct contactless routine environmental disinfection to effectively block potential transmission chains.

Susceptible Population: First, natural language processing analyzes massive epidemic data to monitor public opinion trends and develop intelligent voice consultation robots providing post-traumatic stress disorder counseling to promote rapid public and social recovery post-pandemic (Figure 1). Second, knowledge graph-based scenario analysis assists in improving epidemic control measures. Third, machine learning and natural language processing analyze post-epidemic multimodal health data to optimize existing control measures, strengthen skills and resource reserves of epidemic control institutions, and build intelligent management platforms for "epidemic-normal conversion and emergency integration," health resource scheduling platforms, and resilient supply chains to enhance capacity, efficiency, and quality for future emerging and re-emerging infectious disease prevention and control [2,22,26].

6 Future Trends

Although big data and AI have been widely applied across all stages of COVID-19 emergence and spread (Figure 1), challenges remain. First, achieving interoperable and mutually recognized epidemic information sharing across provinces and application scenarios. Much epidemic control information—including nucleic acid tests, vaccination records, travel codes, health codes, and transit codes—faces issues such as inconsistent system platform interface standards, varied data transmission protocols, mismatched information content, and non-mutual recognition of information carriers across provinces and scenarios. This inevitably affects big data and AI capabilities for reading and processing epidemic information, impacting cross-regional control efficiency and effectiveness. Second, fully mining and integrating the value of epidemic control data. Precise, efficient epidemic control requires comprehensive multi-dimensional information support, yet epidemic data suffers from unclear sources, single dimensions, incomplete integrity, insufficient accuracy, and inadequate timeliness, preventing the legal, secure, and full exploitation of value embedded in massive epidemic data. Future efforts must use modern information technology and AI algorithms for multi-dimensional integration and deep analysis of epidemic data to fully release its enormous value and better support decision-making. Third, strengthening security and privacy protection for multimodal epidemic data. Epidemic control data involves significant sensitive public information, and integration processes make associations between different data clearer and tighter, increasing leakage risks [27]. Future efforts must standardize data collection, transmission, integration, and analysis procedures using blockchain, edge cloud, and privacy computing technologies, clarifying usage conditions, scope, and security responsibility entities [19,22]. Finally, building integrated big data and AI software/hardware systems for epidemic control. Current applications are severely fragmented across epidemic control stages, with "silo" phenomena in interface standards, communication protocols, integration mechanisms, and cross-referencing of results among various technologies and applications. An integrated big data and AI software/hardware system is urgently needed to smoothly and efficiently operate all epidemic control stages, further shortening response times and improving efficiency [22,28-29].

Big data and AI technologies have played positive roles in COVID-19 prevention and control, effectively improving information processing and analysis speed, supporting decision-making, and reducing labor and time costs. This study examined problems in COVID-19 prevention and control, overviewed common big data and AI technologies and application cases, and innovatively analyzed their applications before, during, and after the epidemic using the Haddon model perspective across the three elements of infectious source, transmission route, and susceptible population. The results are significant for clarifying the positive roles and development directions of big data and AI at each epidemic stage, improving COVID-19 prevention and control efficiency and quality, and effectively responding to future emerging and re-emerging infectious disease epidemics.

Author Contributions: GAO Jinghong and WANG Chengzeng conceived and designed the study, analyzed feasibility, wrote the manuscript, revised the paper, controlled quality, and supervised the project. WANG Yanyan, JIANG Shuai, and FU Hang collected and organized background information. DUAN Yanran and WANG Sufan retrieved and organized materials related to big data processing technologies.

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Note: Figure translations are in progress. See original paper for figures.