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Robotic versus manual disinfection of global priority pathogens at COVID-19 dedicated hospitals

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Abstract:

Background: Twelve bacterial families were identified as global priority pathogens by the World Health Organization in 2017, recognizing the greatest threat they pose to human health and the declining antibiotic efficacy. Robotics has emerged as a swift and contactless tool for disinfecting bacterial surface contamination in healthcare facilities, however, head-to-head comparison of disinfection efficacy of robotic versus manual disinfections is limited. This study aimed at comparing how robotic disinfection performs over manual disinfection against the global priority pathogens in the healthcare setting.

Methods: A spraying disinfection robot was developed, and its disinfection efficacy was compared against manual disinfection during July 2020-December 2020. Disinfections were performed on the clinical surfaces and inanimate objects at two hospitals in Nepal using robotic or manual application of a disinfectant (NaOCl). Swab samples from floor, bed, doorknob, and medical devices at both hospitals were collected before and after disinfection and examined for total heterotrophic plate count and bacterial pathogens were identified based on Gram's staining and biochemical characteristics. Disinfection outcomes were reported as log reduction (log_{10} CFU/inch^2) of heterotrophic count and presence or absence of target bacteria. A total of 76 samples were collected from two study sites including major pathogens: *Staphylococcus aureus*, *Escherichia coli*, *Acinetobacter* spp., and *Klebsiella pneumoniae,* among others.

Results: Both robotic and manual disinfection significantly reduced microbial load (log 2.3 to log 5.8) in the hospitals. No pathogens were detected post-disinfection using the robot. The use of robotic disinfection was more effective, significantly reducing more bacterial load (log 5.8) compared to manual disinfection (log 3.95).

Conclusions: Our results showed better efficacy of robotic disinfection compared to manual disinfection of hospital surfaces, and thus contactless robotic disinfection is recommended for disinfecting bacterial contamination of surfaces in the hospital and clinical settings as it favors patient safety against global priority pathogens.

Keywords: bacteria, pandemic, robotics, disinfection, microbial inhibition

BACKGROUND

Healthcare organizations must have contingency plans to manage and control infectious diseases[1]. Human-to-human transmissions of infectious microbes are facilitated by aerosolized droplets, infected hands, and contaminated surfaces[2]. As a response, disinfections of public and healthcare settings are prioritized to prevent future spread[3]. In 2017, the World Health Organization (WHO) catalogued a list of twelve families of bacteria as the global priority pathogens (GPPs), due to the greatest threat they pose to human health and the declining efficacy of antibiotics against the bacteria[4]. Antibiotic resistance (AR) or multidrug resistance (MDR) is a growing global crisis, resulting in over 1.2 million deaths worldwide in 2019, with the United States (US) experiencing around 35,000 deaths per year from resistant infections[5,6]. Drug-resistant infections-related deaths are forecasted to increase to approximately 10 million deaths per year by 2050 if no proactive measures are taken[7]. The bacteria responsible for the most deaths associated with resistance were *Escherichia coli*, *Staphylococcus aureus*, and *Klebsiella pneumoniae* followed by *Streptococcus pneumoniae*, *Acinetobacter baumannii*, and *Pseudomonas aeruginosa*[5], whereas for the US, carbapenem-resistant Enterobacteriaceae, *Clostridioides difficile*, and methicillin-resistant *S. aureus* (MRSA) were implicated as the most common AR/MDR causing deaths[6]. Strategies to address AR/MDR threat include improving antibiotic stewardship, investing in new antibiotic research, and implementing better infection prevention and control measures[8].

Implementation of robotic disinfection in the healthcare and quarantine facilities emerged during COVID-19 pandemic, with a focus on managing the spread of SARS-CoV-2[9]. Based on experience from COVID-19 pandemic, developing risk mitigation strategies with multisectoral collaboration to minimize spread of such contagious infections is paramount for public health protection[10]. Humanoid robots, self-governing vehicles, drones, and other astute robots have also gained increased interest in various sectors, including entertainment, healthcare, security, rescue missions, and space industries[11,12]. Spraying robots are commonly used to spray disinfectants over large outdoor areas, such as public places and residential areas. These robots are operated remotely to avoid personal contact and improve disinfection efficiency[9]. Traditional cleaning and sterilizing systems rely on a human administrator to select and detail a suitable specialist and assign the operator to all target surfaces for the required contact duration. Improvement of these standard tactics necessitates a shift in human behavior, which is often difficult to achieve[13–16]. The use of 'no-contact' or ‘contactless’ automated room cleaning frameworks can help alleviate these concerns[17].

It is well documented that the SARS-CoV-2 virus is primarily spread by intimate personal contact and respiratory droplets, while airborne transmission during aerosol-generating medical procedures is conceivable in healthcare and nonclinical settings. Further, environmental surfaces are more likely contaminated with pathogenic viruses, bacteria, and fungi, which can pose significant public health and safety risks[18–20]. Despite ongoing efforts, AR/MDR amongst bacteria remains a major public health threat in the US and globally[21,22].

It is now evident that higher mortality among COVID-19 patients occurred due to secondary infection or co-infection of bacterial and/or fungal pathogens, which has received inadequate attention[23]. Bacteria have been found to survive on inanimate objects for varying periods[19,23,24]. The duration of bacteria survival on colonized items is directly related to the risk of transmission. The ability of bacteria to colonize and survive in a given object may be influenced by geographical and environmental factors such as temperature, humidity, presence of organic matter, the ability to form biofilms, and infection control measures used[19]. The hospital environment harbors a variety of pathogenic and opportunistic bacteria, including Gram-positive pathogens such as *C. difficile*, methicillin-resistant *S. aureus* (MRSA), vancomycinresistant *Enterococcus* (VRE), and Gram-negative pathogens such as *Pseudomonas*, *Klebsiella*, and *Acinetobacter* spp., and are transmitted through contaminated surfaces[19,23,25–28].

In Nepal, robots were used for communication and serving food and medicine to COVID-19 patients[29]. Disinfecting robots have not yet been established in Nepal to control the pathogens present in hospital settings with COVID-19 patients and other patients with contagious infections. The efficacy of sprayed disinfectants against bacterial pathogens in hospital settings has been inadequately investigated and reported so far. Besides, SARS-CoV-2 infection, there might be other bacteria contributing to morbidity and mortality among COVID-19 patients. This study aimed at measuring disinfection outcomes on frequently touched surfaces before and after disinfection using robotic and manual applications of a common disinfectant, sodium hypochlorite (NaOCl), in the hospitals of Nepal. We hypothesize that robotic disinfection, owing to contactless and error-free application, will outperform manual disinfection of the hospital surfaces and lead to higher reduction in the microbial load. To the best of our knowledge, there is a severe lack of data regarding bacterial colonization of inanimate objects in hospitals during the COVID-19 pandemic. Identifying such bacteria and comparing manual vs. robotic contactless disinfection would guide hospital administrators and public health professionals to mitigate pathogenic bacterial transmission and limit secondary infections and co-infection during times of infectious disease outbreaks.

Materials and Methods

Study design

This cross-sectional quantitative study was conducted from July 2020 to December 2020. The study was designed to compare the disinfection procedures by manual (human) versus robotic applications. This study was divided into two parts: the design and assembly of a disinfectant-spraying robot, and the evaluation of the disinfection by deploying the spraying robot at two COVID-19 dedicated hospitals: KIST Teaching Hospital, Lalitpur, and National Ayurveda Research and Training Center, Kirtipur, Nepal. The latter was designated as an Isolation and Quarantine centre by the Government of Nepal during the COVID-19 pandemic. Both manual and robotic application of disinfectant were performed by healthcare workers and custodians. 0.5 % NaOCl solution was used as a disinfectant.

Specifications and working principle of the robot developed

A remotely controlled robot, capable of spraying NaOCl in hospitals and quarantine settings, was designed and developed (Figure 1). Arduino served as the main processing unit, offering a variety of controls and motions. The mobile application, through a wireless connection, provided users with full control over the robot, enabling effortless movement and NaOCl spraying with just a touch of their finger. The photograph, design flow and coding of the robot are presented in **Figure 1** and its working principles are as follows: The robot ver. 1.0, with a differential drive, uses four 24V DC motors to control each wheel's rotation. It is managed by an Arduino Mega 2560 microcontroller, which controls motor drivers and Bluetooth signals. The DC motors, controlled by an H-bridge L298N driver, can operate in both clockwise and counter-clockwise directions. The Arduino's PWM (Pulse Width Modulation, a technique that enables analog-like results using digital signals by varying the "width" of pulses within a fixed period) input determines the motor driver's speed and direction control. The wooden two-axis arm, used for NaOCl spraying, is operated by a NEMA 17 stepper motor and a MG995 servo motor for horizontal and vertical movement, respectively. A stepper A4988 driver controls the stepper motor for precise arm movement, with two proximity sensors attached for enhanced control. A 12V DC water pump sprays NaOCl, controlled by an on/off relay switch. The robot has two proximity sensors mounted at the front and back. The proximity sensors are used to detect obstacles in the path of the robot and signal the controller if any obstacle is detected. The robot uses a Raspberry Pi Model 3B+ for video streaming. The video, captured by a Raspberry Pi Camera, is broadcast via Wi-Fi to the mobile app. The robot, equipped with an HC-05 Bluetooth module, is controlled via a mobile app using Bluetooth.

The mobile app was created using Flutter and comes with an interface for controlling the robot as well as for viewing the video that is captured by the robot. The robot's power supply is split: one for the DC motors, and the other for the remaining components. The motors, being noisy, are isolated to prevent interference with other components. The isolation is done using optocouplers. Three Buck regulators distribute 5V: one for the high-current Raspberry Pi, one for the DC motor part of the circuit, and one for the remaining components. The Arduino Mega is directly powered by a 12V battery. The robot features two battery indicators: one for the DC motors and another for the rest of the circuit. Notable features of the Version 1.0 robot are a transparent body, wide-body frame structure, differential drive of wheels, low ground clearance, wooden arm, LED indicators for visual inspection, and 180-degree arm movement.

Sample collection and transportation

Surface swabs from the floor, bed (resin) or bench, doorknobs, and medical devices were evaluated for bacterial density and potential pathogens identified before and after disinfection. The robot was used for disinfection at the sampling sites. The effectiveness of robotic disinfection was compared with manual disinfection at a hospital and a quarantine center. The COVID-19-dedicated KIST Teaching Hospital in Lalitpur and the National Ayurveda Research and Training Center, a quarantine/isolation centre in Kirtipur, facilitated robotic disinfection research and sample collections. The study employed the widely used disinfectant, NaOCl. Surface swabs from various objects were collected before and after NaOCl application. Manual disinfection was both facilities' routine cleaning procedure. Robotic disinfection, using a 0.5% NaOCl solution, was performed on separate days and different areas following manual disinfection.

From KIST hospital, samples were collected (in triplicates) from bed, door, doorknob, and hospital instruments (three replicates for each) each day for three days after 30 minutes of disinfectant application. From the National Ayurveda Research and Training Centre's quarantine settings, samples were obtained from 10 beds, 10 doorknobs, 10 floors, and 10 quarantine instruments, and the collection was performed for two days. Sample collection strategies between two collection sites were not same because extra precautions had to be exercised to avoid potential exposures from COVID-19 during sample collection at the National Ayurveda Research and Training Centre as it served as the main quarantine site for COVID-19 patients and limited knowledge existed at that time about potential transmission; thus, only inhibition of microbes was determined as CFU present or absent over the course of two days versus three days for KIST hospital. The duration and sample count varied based on permissions, influenced by disease severity. Collected swabs were stored in saline-filled, cotton-sealed sterile test tubes. Using triple-packing system, the sample tubes were placed in sanitized ziploc containers and stored in an ice box. The samples were transported within 2 h to the Microbiology laboratory at the Central Department of Microbiology, Kirtipur, Nepal.

Heterotrophic plate count and detection of pathogens

The swabs were cultured in MacConkey agar (MA), blood agar (BA), cetrimide agar (CA), and Manitol Salt Agar (MSA). The quadrant streak method, using a whole plate, was employed for culture. After inoculation, the plates were incubated for at least 24 h at 37°C, and colonies were observed and enumerated. The colonies showing significant growth were isolated and used for identification of the bacterium at the species level. The identification of the significant isolates followed multiple standard microbiological methods[25], including morphological appearance of colonies, staining reactions, and biochemical properties.

Data Analysis

Data were recorded in MS-Excel spreadsheets, and SPSS v.22 (IBM Corp., Armonk, NY) and GraphPad Prism 8.4.3 (GraphPad; LaJolla, CA) were used for statistical analysis. Percentages and Chi-square tests were used to evaluate the disinfection efficacy and the p-value < 0.05 was considered statistically significant. Graphs were plotted using Python 3.11 in Spyder.

RESULTS

Testing and validation of the spraying robot

The performance testing and validation of the spraying robot were done at the Institute of Engineering, Tribhuvan University, Nepal. These included spraying robot tasks and achievement testing as well as tasks on the electronic and communication systems of the robot. The working time was 45 min (video stream on) and one h (video stream off). The spray range was between one-two meters covering the spray area of 2-2.5 m^2 per min.

Efficacy of manual application of the disinfectant at the hospitals

At KIST hospital, among 36 samples (three days x 12 samples x three replicates) taken before the disinfection, five samples harbored the pathogens (5/36); the total number of samples that were positive for *S. aureus*, *E. coli*, and *K. pneumoniae* were two, one, and one, respectively. Both samples for *S. aureus* positive were from beds, one *E. coli* positive sample was from the doorknob, and one *K. pneumoniae* positive sample was from a ventilator used in COVID-19 patients' isolation ward. No target pathogens were detected in any of the samples after manual disinfection ($p = 0.023$; **Figure 2**).

The manual disinfection in the quarantine setting was also found to significantly inhibit the pathogens ($p = 0.003$). The pathogens that were isolated were *S. aureus*, *E. coli*, *K. pneumoniae*, and *Acinetobacter* spp. In the study, *S. aureus* was found in seven samples (three from benches, three from floor, and one from hospital stand), *E. coli* in seven samples (three from hospital instruments, four from floor), and *K. pneumoniae* in two samples (from the floor and stand) whereas *Acinetobacter* spp. was found in one sample (from the floor) out of 40 sampling points (**Figures 2, 3**). In total, 17 isolates were isolated from 12 samples (12/40). None of the target bacteria were detected in any samples after disinfection. For the floor, nine pathogens were isolated from six samples (6/10) prior to manual disinfection, indicating the considerable occurrence of the pathogens. After disinfection, two samples (2/6) from the saline stands still contained pathogens, potentially due to manual cleaning errors. Given the small sample size, the impact of manual disinfection on the floor was not statistically significant ($p > 0.05$).

Efficacy of robotic disinfection in quarantine and hospital settings

A total of 10 floor sampling points were identified to apply the robotic disinfection in the quarantine center at the National Ayurveda Research and Training Center due to COVID-19 restriction issued by the center. Prior to disinfection, three isolates of *S. aureus* were obtained from a total of 10 samples. No pathogens were detected following the robotic disinfection (**Figure 2d**).

For three days, three samples per day were taken from the bed, door, floor, and medical devices from the KIST hospital settings. Out of 36 samples, *S. aureus* (two from elevators, three from floor, and one from bed), *E. coli* (one from floor and one from door), *and K. pneumoniae* (one from elevator) were isolated prior to disinfection. However, none of the bacteria were detected in any sample following robotic disinfection (Figure 2). The robotic disinfection was found to significantly eliminate pathogens from all the hospital surfaces (p= 0.02).

Microbial load reduction at the hospital following different disinfection modalities

For manual disinfection, microbial load (CFU/inch^2) decreased significantly (p = 0.002). However, a complete reduction of the microbial load was observed only in 25% of the samples following manual disinfection . The robotic disinfection significantly reduced microbial load in the hospital samples (p = 0.002) with a complete reduction in microbial load observed in 58.33% of the samples (Table 1) , which is more than double the disinfection rate compared to manual disinfection.

As shown in Figures 2 and 3, a reduction in microbial load was observed on the floor surface swab samples in both the manual and robotic applications. The results showed that robotic disinfection had more inhibitory action (reduction up to $\log_{10}$ 5.8 CFU) compared to manual disinfection (reduction up to $\log_{10}$ 3.95 CFU).

Complete inhibition of potential pathogens following disinfection procedures

Among 36 surface swab samples, post-disinfection enumeration of bacterial load revealed that only 25 % (9/36) of swab samples taken after manual disinfection had no bacterial growth, while 58.3 % (21/36) swab samples taken after robotic application of disinfectants in the hospital inhibited bacterial growth (Table 1). This implies superior performance of robotic disinfection of the hospital surfaces over manual disinfection. Before disinfection, certain surfaces in the hospital were found contaminated with potentially pathogenic bacteria including *S. aureus*, *E. coli*, *K. pneumoniae,* and *Acinetobacter* spp. However, none of the surfaces were found contaminated after the disinfection, indicating that the surface disinfectants applied in the hospital and quarantine centre were effective (Table 2). However, microbial load was not determined in the quarantine settings, albeit presence or absence of CFUs were determined pre- and post-disinfection (Table 2), due to the risk of SARS-CoV-2 transmission as there were many COVID-19 cases during the sampling schedule. This was crucial as we wanted to minimize the risks of SARS-CoV-2 transmission while sampling the surfaces and handling the samples.

DISCUSSION

The results of this study highlight the crucial role of robotics in managing global priority pathogens that are of greatest threats to public health and safety in the healthcare setting and in the context of the COVID-19 pandemic. The chemical disinfectant, NaOCl, used in the hospital and quarantine settings was demonstrably effective under both manual and robotic applications. Notably, however, the use of the robotic disinfection system resulted in a higher microbial load reduction when compared to manual disinfection. This can be attributed to the precision application by the robot; they can be programmed to follow precise disinfection procedures, reducing the chance of human errors that can occur with manual application[30,31]. This underscores the importance of automatic, contactless disinfection procedures in infection control within the healthcare setting.

Chemical disinfection is a critical tool for preventing infection, and research into how to assure the efficacy of disinfectants and the disinfection process, as well as when, how, and where to use disinfection precautions, is a never-ending decision that involves an interdisciplinary team effort[32]. Healthcare workers frequently become ill and lose their lives due to infectious diseases and more so during pandemics[33]. Contactless cleaning could benefit healthcare workers dealing with contagious infections. The implementation of contactless cleaning methods, such as robotic disinfection systems, could provide a swift and safer approach for healthcare workers dealing with contagious infections.

Prior to the application of both disinfection systems, swab samples revealed the presence of the WHO priority pathogens including *E. coli*, *S. aureus*, *K. pneumoniae*, and *Acinetobacter spp*. Following the disinfection processes, most of these organisms were effectively inhibited, resulting in a significant decrease in the microbial load. The reduction of the microbial load was significant, and a complete reduction occurred in 58.33% of the total samples after the robotic disinfection whereas complete inhibition was observed in only 25% of the samples following manual disinfection. The microbial load reductions in bed, floor, door, and hospital instruments were higher for robotic disinfection compared to manual disinfection. Robotic disinfection demonstrated greater effectiveness (higher median reductions) for the samples collected from the doors and floors compared to manual disinfection. This might be related to the potency of disinfection maintained in the cleaning process. Overall, the variability in log-reduction across samples could be related to material surfaces, environmental and procedural factors. For example, the porous surfaces in bed may likely allow microbes to avoid disinfectant that may lead to inconsistent results[34]. However, this suggests that the application of disinfectant using a robot is more effective than manual application in hospital and quarantine settings for reducing global priority pathogens and the overall microbial load. This further underscores the potential benefits of robotic disinfection systems in infection control. A report suggested that typical manual cleaning and disinfection techniques in hospitals are generally inadequate, which could be related to failure to follow disinfectant manufacturers' guidelines or the absence of antimicrobial activity of some disinfectants against healthcare-associated infections[13], while robots have been lauded for taking on dangerous and unsanitary work, frequently in adverse settings[35].

Contaminated hospital surfaces are a well-known cause of common-source infection[26]. Furthermore, hospitalization in a room where the previous patient had been colonized or infected with certain pathogen has been shown to increase the likelihood of the subsequent occupant being colonized or infected with the same pathogen[35,36]. Microbiological assessment of surfaces helps determine the efficacy of cleaning and disinfection procedures[37]. Robots can provide a contact-free approach when pathogens in question are extremely infectious such as global priority pathogens and coronaviruses, among others. Several robots, notably coronavirus robots, have been utilized in quarantine enforcement, sanitizing public spaces, identifying infected people, managing infectious items, and for other tasks[38].

Our findings are particularly significant in the context of the pandemic situations and could have far-reaching implications for infection control in hospitals and quarantine centres. The use of robotics for disinfection reduces the need for human involvement, thereby reducing the risk of disease transmission[39,40]. This highlights the potential of robotics in enhancing safety and efficiency in infection control within healthcare and clinical settings.

This research highlights the vital role of robotics in managing infectious bacterial diseases, especially during the COVID-19 pandemic in Nepal. Two key findings emerged from this study: the presence of global priority pathogens in the Nepalese hospital environment and the superior efficacy of robotic disinfection compared to manual disinfection. While we were successful in developing a user guided robot and demonstrated the proof-of-concept of its improved disinfection performance compared to manual disinfection, future efforts to automatize the robot would be crucial to minimize personnel labor, time and cost of disinfection while improving disinfection efficacy.

CONCLUSIONS

While both the manual and robotic disinfection methods significantly reduced pathogenic bacterial burden from the surfaces and inanimate objects in two hospitals, our results showed that the robotic application of disinfectant achieved a higher reduction in the bacterial load. This confirmed our hypothesis that robotic disinfection, owing to contactless and error-free application, significantly outperformed manual disinfection of the hospital surfaces. While this pilot study was conducted in two hospitals in Nepal, future research could include viral and fungal pathogens, too, and determine the efficacy of robotic disinfection in public and private hospitals and clinics in other regions, cities, and villages of Nepal. Nonetheless, the utilization of robotics for disinfection of surfaces may help execute swift and effective disinfection of healthcare facilities to promote public health and safety.

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CRediT authorship contribution statement

Conceptualization: Prabin Dawadi, Sayara Bista

Funding acquisition: Prabin Dawadi, Sayara Bista, and Dev Raj Joshi

Methodology: Prabin Dawadi, Sayara Bista, Kamal Darlami, and Dev Raj Joshi

Sample collection and transportation: Gopiram Syangtan, Prabin Dawadi, Arun Bahadur Chand

Investigation: Prabin Dawadi, Sayara Bista, Gopiram Syangtan, Kamal Darlami, Shrijana Bista, Dev Raj Joshi

Data curation: Prabin Dawadi, Sayara Bista, Gopiram Syangtan, Kamal Darlami, Mohammad Ataullah Siddiqui, Dev Raj Joshi, Lok R. Pokhrel

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Revision: Dev Raj Joshi, Lok R. Pokhrel

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Conflict of Interests

The author(s) declare no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

Data availability

Any queries regarding the research data will be addressed by the corresponding author(s) upon reasonable request.

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Figures and Tables

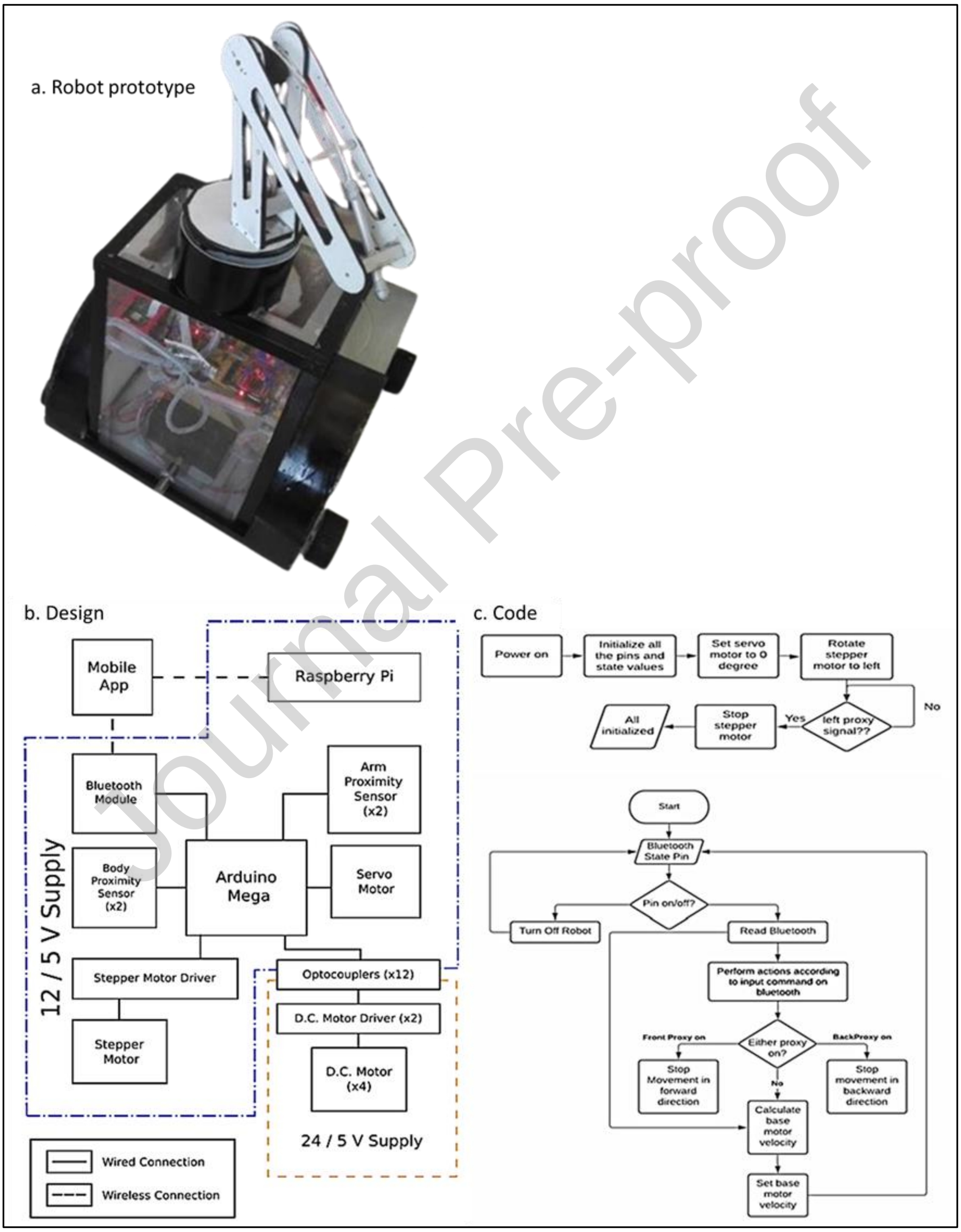

Figure 1. Robot prototype (a), design (b) and coding used (c) for the operation of the disinfection robot used in this study.

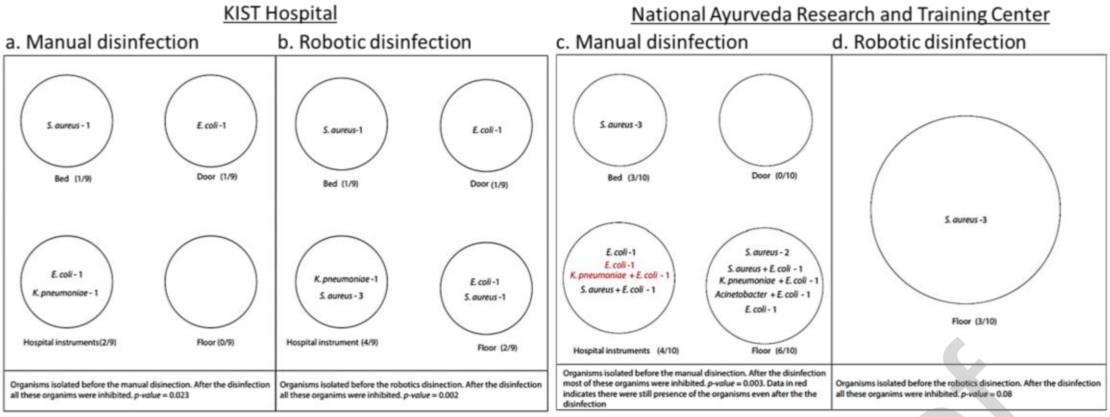

Figure 2. Manual disinfection (a) versus robotic disinfection (b) of priority pathogens from different areas at the KIST hospital, and manual disinfection (c) versus robotic disinfection (d) at the National Ayurveda Research and Training Center, Nepal. Areas sampled were bed, door, floor and hospital instruments. The numerals denote the number of samples that tested positive for a given bacteria out of 9 samples analyzed for KIST hospital and 10 samples analyzed for National Ayurveda Research and Training Center.

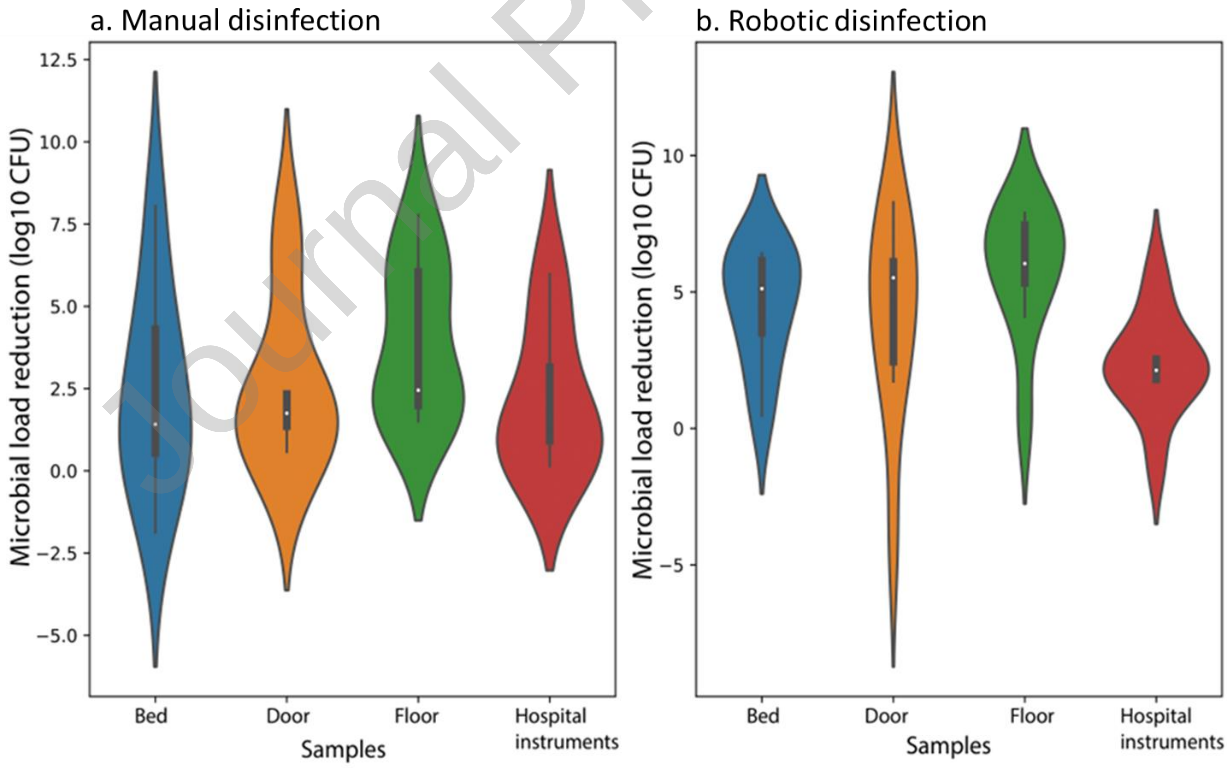

Figure 3. Average microbial load reduction (log10 CFU/inch^2) by manual (a) and robotic application (disinfection robot version 1) (b) using the disinfectant, NaOCl, at the KIST hospital.

Table 1: Manual and robotic disinfection rates (log10 CFU/inch^2) at the KIST hospital, Nepal.

Sample ID	log10 CFU/inch^2 (before)	log10 CFU/inch^2 (after)	Reduction (log)	*p*-value
B1	1.1x10^6	2.3 x 10^5	0.64	0.002
B2	1.51x10^8	9 x 10^5	1.22	
B3	1.61x10^8	3.99 x 10^5	1.61	
D1	2.57 x 10^5	1.1x10^4	1.36	
D2	9.8 x 10^5	2.63x10^5	0.58	
D3	3.96 x 10^5	9x10^3	1.65	
F1	9.8x10^5	3.7x10^3	2.42	
F2	2.85x10^5	9x10^3	1.51	
F3	9x10^5	3.2x10^3	2.45	
M1	1.35x10^8	1.2x10^6	1.05	
M2	1.5x10^8	1.5x10^7	1	
M3	TNTC	1.65x10^8	-	
B4	1.1x10^8	0	8.04	
B5	TNTC	6x10^5	-	
B6	1.2x10^8	4.5x10^3	4.38	
D4	7.5x10^5	3.5x10^3	2.33	
D5	4.5x10^7	0	7.65	
D6	1.3x10^6	0	6.11	
F4	9x10^5	9.1x10^3	1.99	
F5	1.19x10^6	0	6.07	
F6	6x10^7	0	7.77	
M4	1.1x10^8	1.06x10^4	3.84	
M5	TNTC	1.43x10^6	-	
M6	1.42x10^8	1.8x10^7	0.89	
B7	1.03x10^6	7.8x10^7	-1.87	
B8	1.89x10^4	0	4.27	

B9	1.01x10^4	5.6x10^3	0.26	
D7	3.4x10^5	6.7x10^5	-.29	
D8	5x10^7	8.9x10^5	1.75	
D9	1.57x10^6	1.23x10^4	2.11	
F7	4.9x10^5	6x10^3	1.91	
F8	2.2x10^5	0	5.34	
F9	1.1x10^6	0	6.04	
M7	9.8x10^5	7x10^5	0.14	
M8	TNTC	7.6x10^3	-	
M9	9.5x10^5	0	5.98	
Complete inhibition by manual disinfection = 9/36 (25%)				
B1	1.31x10^6	0	6.11	0.002
B2	1.9x10^6	9x10^3	2.32	
B3	TNTC	1.78x10^4	-	
D1	2.4x10^7	1.29x10^4	3.26	
D2	4x10^5	0	5.60	
D3	0	9x10^3	-3.95	
F1	8x10^5	0	5.90	
F2	1.23x10^6	5.6x10^5	0.34	
F3	1.28x10^4	0	4.10	
M1	1.34x10^6	9.8x10^3	2.13	
M2	1.67x10^4	2.33x10^5	-1.14	
M3	9.8x10^5	1.37x10^4	1.85	
B4	1.65x10^6	0	6.21	
B5	2.67x10^6	0	6.42	
B6	2.04x10^4	6.8x10^3	0.47	
D4	3.31x10^5	6.2x10^3	1.72	
D5	1.89x10^8	0	8.28	
D6	2.53x10^6	9x10^3	2.45	

F4	6.1x10^7	0	7.79	
F5	7.9x10^7	0	7.89	
F6	2.1x10^7	0	7.32	
M4	1.08x10^4	0	4.03	
M5	9.3x10^5	3.7x10^3	2.40	
M6	4.3x10^5	6.8x10^3	1.80	
B7	8x10^3	0	3.90	
B8	1.62x10^4	0	4.20	
B9	1.1x10^6	0	6.04	
D7	2.19x10^7	0	7.34	
D8	1.26x10^6	0	6.10	
D9	3.37x10^5	0	5.52	
F7	2.80x10^7	0	7.44	
F8	2.19x10^5	0	5.34	
F9	1.1x10^6	0	6.04	
M7	4.4x10^5	0	5.64	
M8	1.24x10^6	3.7x10^3	2.53	
M9	3.88x10^5	6.8x10^3	1.76	
Complete inhibition by robotic disinfection = 21/36 (58.33%)				

M denotes different devices such as elevators, incubators, saline stands, and ventilators; B denotes bed; F denotes floor; D denotes doorknobs; TNTC denotes too numerous to count.

Table 2: Manual (top panel) and robotic disinfection (bottom panel) of the floor at the National Ayurveda Research and Training Center, Nepal.

Manual disinfection				
Sample ID	Before	After	Pathogen	*p*-value
QF1	Growth	No growth	*S. aureus*	0.193
QF2	Growth	No growth	*S. aureus*	
QF3	Growth	No growth	*S. aureus* and *E. coli*	
QF4	No growth	No growth	-	
QF5	No growth	No growth	-	
QF6	No growth	Growth	*E. coli* and *K. pneumoniae*	
QF7	No growth	Growth	*E. coli* and *Acinetobacter* spp.	
QF8	No growth	No growth	-	

QF9	No growth	No growth	-	
QF10	Growth	No growth	*E. coli*	

Robotic disinfection				
Sample ID	Before	After	Pathogen	*p*-value
QF1	No growth	No growth	-	0.081
QF2	No growth	No growth	-	
QF3	Growth	No growth	*S. aureus*	
QF4	No growth	No growth	-	
QF5	Growth	No growth	*S. aureus*	
QF6	No growth	No growth	-	
QF7	No growth	No growth	-	
QF8	Growth	No growth	*S. aureus*	
QF9	No growth	No growth	-	
QF10	No growth	No growth	-	

QF denotes quarantined floor.

Graphical abstract

Highlights

- WHO global priority pathogens pose greatest threat to public health.
- Robotic versus manual disinfection of surfaces were examined for two COVID-19 hospitals in Nepal.
- Both robotic and manual disinfection could inhibit microbial load (log 2.3-log 5.8) in both hospitals.
- Robotic disinfection was more effective compared to manual disinfection (log 5.8 vs. log 3.95).
- Contactless robotic disinfection is recommended over manual disinfection for improved patient safety.