Journal of Hospital Infection 139 (2023) 113–120

Available online at www.sciencedirect.com

Journal of Hospital Infection

journal homepage: www.elsevier.com/locate/jhin

Use of thermal imaging to measure the quality of hand hygiene

C. Wang [a,*], W. Jiang [b], K. Yang [c], Z. Sarsenbayeva [d], B. Tag [e], T. Dingler [c], J. Goncalves [c], V. Kostakos [c]

[a] Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands
[b] Department of Computer Science and Technology, Anhui Normal University, Wuhu, China
[c] School of Computing and Information Systems, The University of Melbourne, Melbourne, Australia
[d] School of Computer Science, University of Sydney, Sydney, Australia
[e] Faculty of Information Technology, Monash University, Melbourne, Australia

ARTICLE INFO

Article history:
Received 8 February 2023
Accepted 11 May 2023
Available online 8 June 2023

Keywords:
Thermal camera
Ultraviolet light
Hand hygiene
World Health Organization

SUMMARY

Objectives: Hand hygiene has long been promoted as the most effective way to prevent the transmission of infection. However, due to low compliance and low quality of hand hygiene reported in previous studies, constant monitoring of hand hygiene compliance and quality among healthcare workers is crucial. This study investigated the feasibility of using a thermal camera with an RGB camera to detect hand coverage of alcohol-based formulation, thereby monitoring the quality of hand rubbing.
Methods: In total, 32 participants were recruited to participate in this study. Participants were required to perform four types of hand rubbing to achieve different coverage of the alcohol-based formulation. After each task, participants' hands were photographed under a thermal camera and an RGB camera, while an ultraviolet (UV) test was used to provide the ground truth of hand coverage of alcohol-based formulation. U-Net was used to segment areas exposed to alcohol-based formulation from thermal images, and system performance was evaluated by comparing differences in coverage between thermal images and UV images in terms of accuracy and Dice coefficient.
Results: This system found promising results in terms of accuracy (93.5%) and Dice coefficient (87.1%) when observations took place 10 s after hand rubbing. At 60 s after hand rubbing, accuracy and Dice coefficient were 92.4% and 85.7%.
Conclusions: Thermal imaging has potential for accurate, constant and systematic monitoring of the quality of hand hygiene.

Introduction

Hand disinfection — a major component of appropriate hand hygiene — is the most effective way to prevent healthcare-associated infections (HAIs) and reduce their transmission [1–3]. HAIs are among the most crucial patient-safety challenges in healthcare settings [4]. They increase hospital length

* Corresponding author. Address: Faculty of Industrial Design Engineering, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, the Netherlands.
E-mail address: C.Wang-16@tudelft.nl (C. Wang).

https://doi.org/10.1016/j.jhin.2023.05.016

of stay, costs, morbidity and mortality considerably [5,6]. In 2009, the World Health Organization (WHO) issued the 'WHO guidelines on Hand Hygiene in Health Care', providing a thorough review of evidence on hand hygiene in health care and specific recommendations to improve practices in healthcare settings [2]. The guidelines recommend two standard hand hygiene procedures: handwashing with soap and water for visibly soiled hands, and hand rubbing with alcohol-based formulation for routine decontamination of hands for all clinical indications [2].

However, research has found that the quality of hand hygiene in healthcare settings is generally unsatisfactory [7–9]. Szilágyi *et al*. reported that only 72% of healthcare workers (HCWs) could adequately clean all hand surfaces immediately after hand hygiene training [9]. As hand rubbing with alcohol-based formulations has been widely adopted into routine clinical practice [2], precise measurement of the quality of hand rubbing, and the provision of feedback to HCWs regarding their performance are essential to promote good hand hygiene in healthcare environments.

Measuring the quality of hand rubbing in healthcare settings is challenging [10]. Direct observation by trained auditors is considered the gold standard for monitoring both hand hygiene compliance and quality, but its rigor is limited by personnel time and expense, insufficient sample sizes and the Hawthorne effect [11]. Recently, researchers measured the quality of hand hygiene by tracking the compliance of HCWs with the WHO's six-step hand hygiene procedures using environmental and wearable sensors [7,12–17]; however, their techniques were proxy measures to detect the quality of hand hygiene among HCWs. Nevertheless, researchers attempted to quantify hand coverage during hand rubbing and handwashing procedures [18,19]. Ultraviolet (UV) tests have been widely used for medical hand hygiene training of HCWs to highlight regions that have been cleaned insufficiently after hand rubbing. However, as UV tests require fluorescent dye, which often leaves residual which affects follow-up measurements, and UV lamps, they cannot be incorporated easily into the daily routines of HCWs.

Bernard *et al*. [20] found that surface temperature measurements can be affected by the presence of topically applied substances, which can be detected using infra-red thermal imaging. Alcohol-based formulations typically consist of 60–80% ethanol, which evaporates at room temperature and cools hand surfaces. As a result, several studies have proposed the use of thermal imaging to assess the quality of hand hygiene. Boyce and Martinello [21] observed significant decreases in mid-palm, finger and thumb temperatures using thermal imaging after participants performed hand hygiene. Similarly, Smieschek *et al*. [22] utilized a thermal camera to capture images of subjects' hands, dividing each hand into 20 segments. By comparing the temperature differences between corresponding segments, their system estimated the segment-level surface coverage of alcohol-based formulations. However, to the authors' knowledge, a precise coverage comparison between thermal imaging and UV tests or microbiological tests has not been reported in the literature. Additionally, the time window for which thermal imaging can accurately detect the surface coverage of alcohol-based formulations, as hands initially cool down after hand rubbing and then gradually warm up again, remains unclear.

Methods

Study design and participants

Thirty-two participants were recruited through the institution's mailing lists and using snowball recruitment with an equal number of women and men. All participants were students or staff at the study institution, and their ages ranged between 18 and 27 years [mean 22.8 years, standard deviation (SD) 2.1 years]. The majority of participants (27/32, 84.4%) had not received formal hand hygiene training in the previous 3 years and were not familiar with the formal hand hygiene protocol. The entire experimental procedure lasted for approximately 130 min, including briefing and debriefing. This study was approved by the Human Ethics Advisory Group at the study institution.

Before the experiment, participants completed a questionnaire about allergic reactions to alcohol-based formulations and UV light. Upon arrival at the laboratory, participants were briefed on the purpose of the study, and their written consent to participate was obtained. Next, the participants received training in the WHO's six-step handrub procedure. This involved explanation of the steps of the procedure, watching an instructional video provided by WHO [23] three times, and performing hand rubbing along with the instructional video.

After the training session, participants proceeded to complete the experimental tasks. Before each task, participants rinsed their hands to remove residual fluorescent dye and dried their hands with tissues. Next, they rubbed their hands with hand warmers for 1 min to rewarm their hands to body temperature [24]. Both thermal and RGB images were taken as baseline images before depositing alcohol-based formulation on participants' hands. After that, participants performed the experimental tasks and placed their hands on observation pegboards for 60 s while they were observed by a thermal camera. Finally, the UV lamp was turned on above the participants' hands, and a photograph was taken using the RGB camera. The devices used in the experiment were sanitized between participants for hygiene reasons. More details of the experiment flow are shown in Figure 1.

Thirty different tasks were designed in line with four task types mentioned in Appendix Section B for both sides of the participants' hands, as well as task descriptions for each task and visualized surface coverage examples. However, as participants were required to keep their hands on the pegboards during the 60-s observation period, this would had led to a total experimental duration of 180 min, and potentially caused participant fatigue. Therefore, the duration of the experiment was reduced by only observing one side of each participant's hands (either palmar side or dorsal side) for the tasks of separated WHO handrub steps. As a result, each participant completed 21 of 30 possible tasks. Specifically, tasks 5–13 (individual handrub steps, dorsal) and tasks 20–28 (individual handrub steps, palmar) were completed by half the cohort.

Segmentation of RGB and thermal images

A deep learning neural network – U-Net, one of the most widely-used biomedical image segmentation algorithms – was

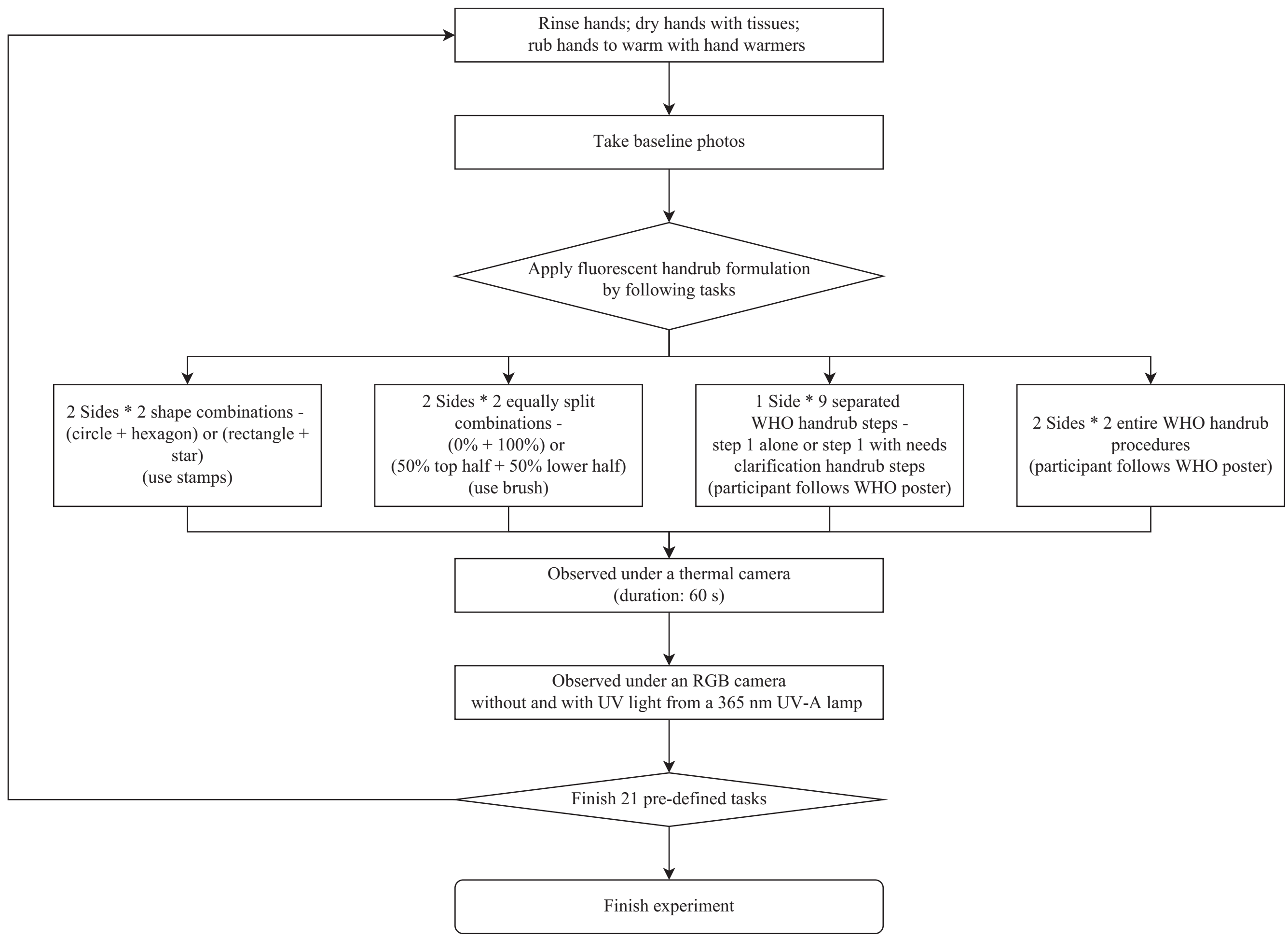

Figure 1. Experiment flow. WHO, World Health Organization; UV, ultraviolet.

adopted to segment: (i) hand areas from RGB images; and (ii) covered areas from thermal images.

The same network structure (shown in Appendix Figure 5) was used for both segmentation tasks. The inputs to the model for task 1 (segment hand areas from RGB images) are shown in Figure 2. The inputs of task 2 (segment areas covered by alcohol-based handrub from thermal images) were combined with the baseline image, observation image and their differences. The background may be noisy when adopting thermal imaging in healthcare settings; therefore, the segmented hand areas generated by task 1 were used to remove the background information from the inputs of task 2. More details are shown in Figure 2. To increase the size of the dataset, the images were flipped horizontally for data augmentation.

Both models were trained with Combo loss by combining Cross-Entropy loss and Dice loss [25]. The models were implemented and trained in Pytorch with a single Nvidia GeForce RTX 3080 super (12 GB RAM). Both models were trained for 30 epochs with a batch size of 8. The input images were resized to $3 \times 483 \times 322$ pixels (16% of the original image). RMSprop optimization was used, with an initial learning rate of 10^{-5}, weight decay of 10^{-8} and momentum of 0.9. The learning rate schedule was used on this basis: if the Dice coefficient on the validation set is not increased for two epochs, the learning rate will decay by a factor of 0.1.

Statistical analysis

Accuracy and Dice coefficient of both segmentation tasks were measured to assess the performance of the proposed systems and five-fold cross-validation was used to check their generalizability. For task 1, the U-Net segmented hand areas were compared with manually segmented hand areas. For task 2, as previous work has shown that fluorescent dye highlights the areas of the hand surface that are disinfected adequately with acceptable accuracy (95% sensitivity and 98% specificity), the coverage difference between results detected by UV images and thermal images was compared. More details are provided in Appendix Section C.2 [26].

For each image (including both left and right hands), accuracy was calculated across all classes (task 1, hand areas and background; task 2, hand areas covered or uncovered with alcohol-based formulation). The Dice coefficient was calculated for regions of interest (task 1, hand areas; task 2, hand areas covered with alcohol-based formulation). However, as hands in several tasks will be either fully covered or not

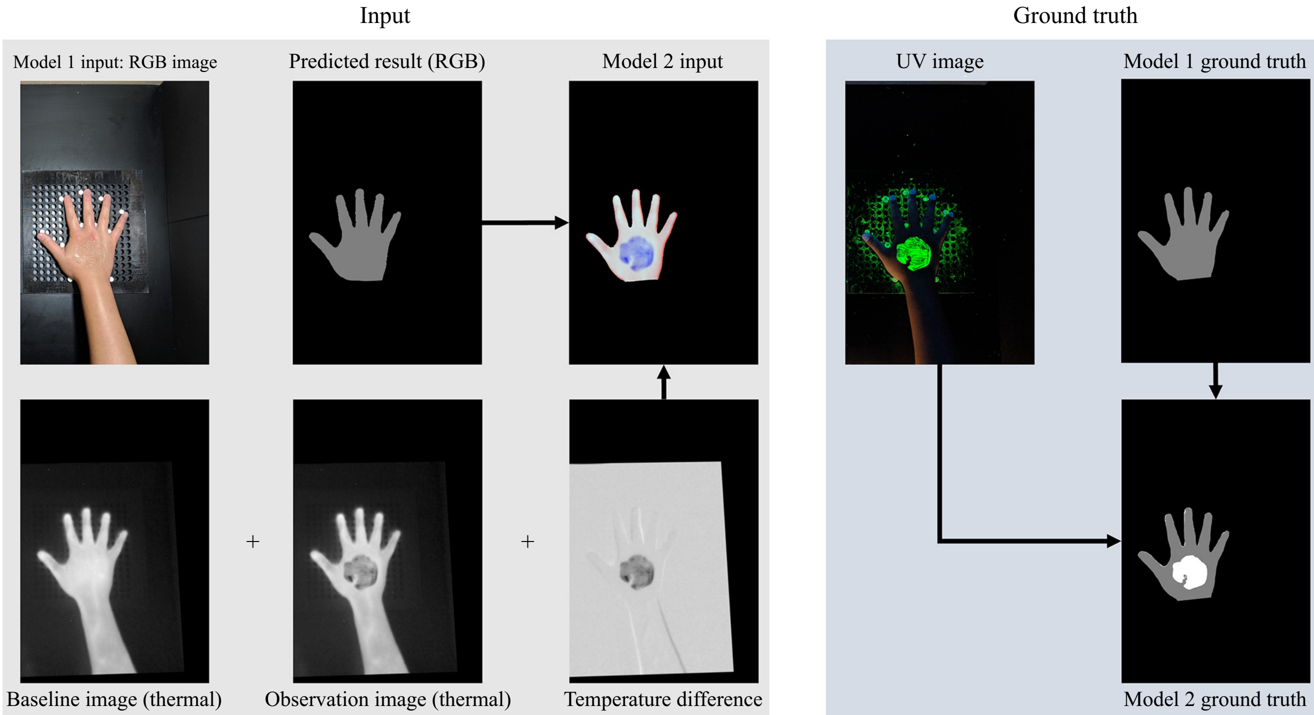

Figure 2. Required inputs of the proposed models. UV, ultraviolet.

covered by alcohol-based formulation (e.g. the task of Step 1 alone; more details shown in Appendix Section B.2), 0% coverage will raise division by zero errors when calculating the Dice coefficient. Therefore, the Dice coefficient was calculated as:

$$\frac{2 \times \mathit{True\ Positive}\ (TP) + \varepsilon}{2 \times TP + 2 \times \mathit{False\ Positive}\ (FP) + 2 \times \mathit{False\ Negative}\ (FN) + \varepsilon}$$

where $\varepsilon = 0.001$ to prevent division by zero errors.

Due to heteroscedasticity in the data, Welch's analysis of variance (ANOVA) and the Welch—Satterthwaite approximation for degrees of freedom were adopted [27]. Statistical analyses were conducted using Python Version 3.6.8 and statsmodels Version 0.9.0.

Results

Segmentation performance

The data of three participants (Participants 1, 13 and 22) were discarded because they did not follow the study protocol precisely (e.g. failed to wash out residual UV dye, or did not keep their hands still during the observation period). Considering the accuracy of the system, it is important to note that the timing of measurement matters. As alcohol evaporates from the participants' hands, it causes a temporary reduction in temperature. This means that if the thermal observation happens a long time after the alcohol is applied, there may be no observable effect. Given these constraints, accuracy and Dice coefficient were reported at the 10-s observation time (i.e. the thermal imaging observation happens 10 s after participants place their hands on the pegboards), due to its highest accuracy. The subsequent section reports the effect of increasing this time window to 60 s.

For the model of task 1, mean accuracy and Dice coefficients throughout five-fold cross-validation were 99.6% (SD=0.0003) and 97.2% (SD=0.003), respectively. More details are shown in Figure 3a. In order to validate the accuracy of thermal imaging to detect the coverage of alcohol-based formulation, the performance (in terms of accuracy and Dice coefficient) of thermal imaging was summarized across participants, hand sizes and tasks (coverage ranges from 0% to 100%) to ensure the reliability and validity of the results.

The system recognized hand areas covered with alcohol-based formulation with mean accuracy of 93.5% (SD=0.046) and mean Dice coefficient of 87.1% (SD=0.195) for all participants across all experiments. Accuracies for each participant for different tasks were grouped, and the results are presented in Figure 3b. Of these, the highest mean accuracy was 96.0% for Participant 25, and the lowest mean accuracy was 84.9% for Participant 32. Participant 7 had the highest mean Dice coefficient (96.0%), and Participant 32 had the lowest mean Dice coefficient (64.0%).

Furthermore, the effect of hand size on accuracy was measured. As a fixed amount of alcohol was used per participant task (3 mL as recommended by [28]), there was less alcohol per unit area for participants with larger hands. Thus, participants were grouped in terms of hand length: $160 \leq XS < 171$ mm, $171 \leq S < 182$ mm, $182 \leq M < 192$ mm, and $192 \leq L < 204$ mm, and mean accuracy for each participant was considered as one data point (shown in Figure 3c). One-way ANOVA did not show a significant difference in system accuracy ($F_{3,25}$=1.302, P=0.295) or Dice coefficient ($F_{3,25}$=0.662, P=0.583) for different hand size groups.

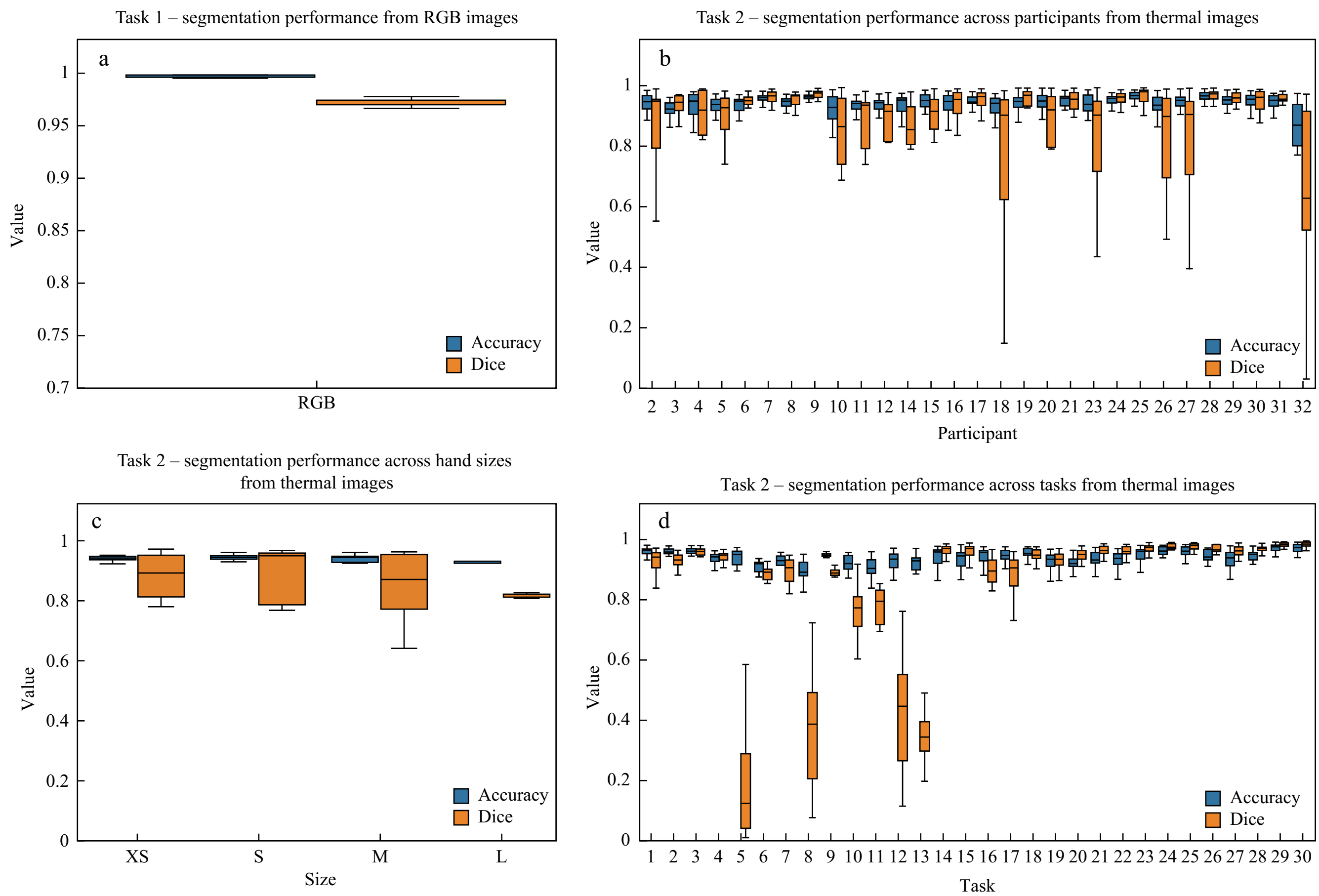

Figure 3. Classification accuracy and Dice coefficient of participants, hand sizes and tasks.

Mean accuracy for each task was measured by summarizing results across all participants (shown in Figure 3d). Of these, task 30 had the highest mean accuracy of 96.3%, and task 8 had the lowest mean accuracy of 88.7%. Furthermore, task 30 had the highest mean Dice coefficient of 97.7%, and task 5 had the lowest mean Dice coefficient of 17.6%.

As seen above, Dice coefficients showed several dramatic drops for some participants and tasks, even though accuracy was still >90%. This phenomenon may be associated with the small sizes of the areas that alcohol-based formulations covered. Therefore, Spearman's correlation test was applied to examine the correlation between Dice coefficient and size of the area covered by alcohol-based formulation. For each participant, the mean percentage area covered with alcohol-based formulation across all tasks varied from 34.0% to 73.6%, and a strong positive correlation was found with Dice coefficient (0.840, $P<0.001$). For each task, the mean percentage area covered with alcohol-based formulation across all participants varied from 6.1% to 94.2%, and a strong positive correlation was found with Dice coefficient (0.967, $P<0.001$). These findings suggest that thermal imaging may not be able to identify areas with small sizes and near edges because of the limited resolution of thermal cameras and the imperfect alignment between baseline and observation images.

Effects of varying observation

In this study, participants were required to place their hands on the observation pegboards for 60 s after completing all 21 tasks. Throughout this 60-s observation period, the effect of gradual hand rewarming on system performance was measured. Accuracy and Dice coefficient were calculated for each participant, and then grouped by observation time across all 30 participants. Due to the computational requirements of the analysis, the thermal imaging results every 5 s from 0 s delay (images captured immediately after participants placed their hands on the observation pegboards) to 60-s delay were analysed, as shown in Figure 4.

Maximum mean accuracy of 93.6% was found at 10 s, where all mean accuracy values were >92% across the 60-s observation period. Meanwhile, all mean Dice coefficients were >85% between 0 s and 60 s, with the highest mean Dice coefficient of 87.4% occurring at 35 s. More details are shown in Figure 4.

Across the 60-s observation period, accuracy and Dice coefficient decreased gradually over time. Therefore, correlation between observation time and system performance was evaluated using Spearman's correlation test. The correlation values between observation time and accuracy and Dice coefficient were -0.275 (P=0.026) and -0.034 (P=0.785), respectively. Although it is recommended that thermal images

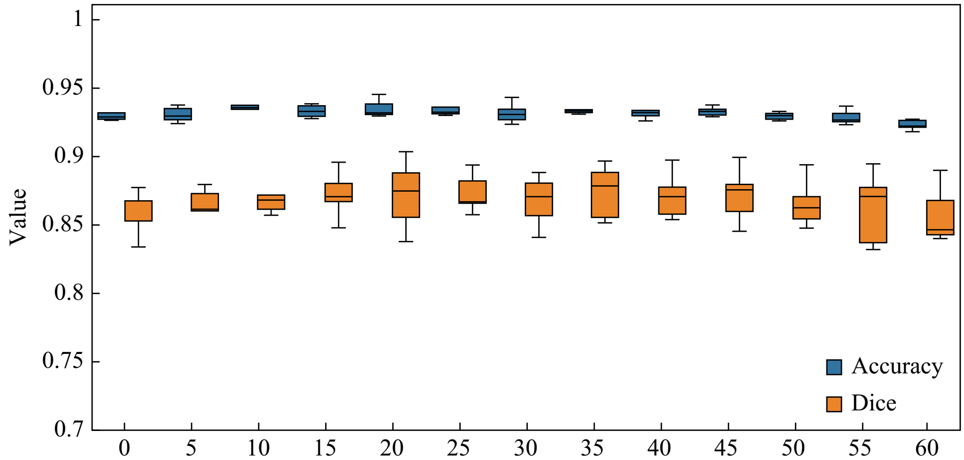

Figure 4. System performance of accuracy and Dice coefficient across 60 s of observation.

should be collected as soon as possible because of the weak negative correlation between observation time and system performance, thermal imaging operated effectively throughout the 60-s observation period.

Discussion

Adopting thermal imaging in healthcare settings

This study primarily aimed to demonstrate the feasibility and functionality of the method, rather than its actual implementation in healthcare settings. In real-world deployments, users would not need to keep their hands motionless for 60 s, as the evaluation could potentially be completed within a few hundred milliseconds. Furthermore, recognizing the impracticality of maintaining users' hand positions between two observations, three alternative approaches are proposed below to adopt thermal imaging in healthcare settings to record baseline and observation images (illustrated in Figure 5).

Approach (a) involves the provision of a Graphical User Interface (GUI), which shows a wireframe RGB image with superimposed hand contours. The GUI would instruct HCWs to place their hands in the same position when taking baseline images and observation images after hand rubbing (details shown in Figure 5 [29]). However, this may run into issues with hand misalignment, which may result in classification mistakes and poorer system performance.

Approach (b) involves sectioning hands into segments and then comparing the temperature differences of the same segments between the baseline images and observation images (details shown in Figure 5 [22]). While HCWs are aware that a certain segment is exposed to alcohol-based formulation, they

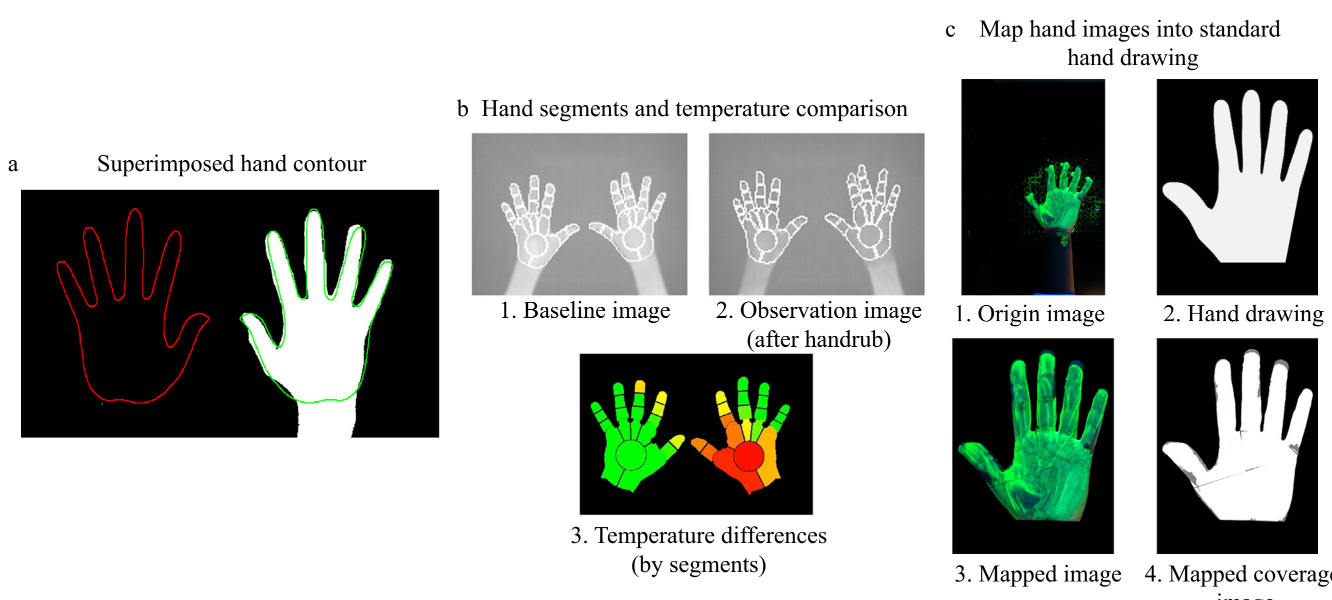

Figure 5. Alternative approaches for deploying thermal imaging in healthcare settings. Approach (a) is based on Smieschek *et al.* (2019) [29], Approach (b) is based on Smieschek *et al.* (2016) [22], and Approach (c) is based on Wang *et al.* (2022) [18].

are unable to identify which parts within the segment are unexposed due to the lack of precise coverage information that comes with this solution.

Approach (c) involves the avoidance of calculation of temperature differences for segments, and instead, mapping hand segments to a standard hand drawing (details shown in Figure 5 [18]). The system first splits recognized hand regions and hand drawings into 18 segments based on the landmarks generated by MediaPipe and finger-web points [30]. Next, the segments of the hand regions are matched and mapped to the corresponding segments of the hand drawings. After that, the system can calculate temperature differences without losing coverage information. As a result, HCWs can recognize areas that have been missed, and the visual intervention could help them to improve their hand hygiene. This approach may offer extensive information inside hand segments and is more resilient to hand misalignment than the other two approaches.

Limitations

As thermal imaging needed to be validated in the context of measuring the quality of hand hygiene, this study was conducted in a controlled laboratory environment rather than as a field study in a healthcare setting. It is acknowledged that when adopting thermal imaging in healthcare settings, more factors must be taken into account.

The system uses thermal imaging to track temperature drops caused by alcohol-based formulations; hence, it is not able to evaluate the efficacy of handwashing with water and soap, because water may cause consistent temperature drops across all hand surfaces. Instead, in order to evaluate the quality of handwashing, previous studies have used sensors to track HCWs' adherence to the WHO's six-step hand hygiene technique [13–17]. Moreover, the performance of the system may be affected by variations in hand hygiene technique, such as changes in order and the inclusion of extra steps, which necessitates further investigation.

Also, as the system is based on thermal imaging, any changes in temperature could affect the performance of the system. Of these, hand temperature is the most important and diverse factor. In this study, participants' hand temperature was controlled to start at approximately 36 °C, using hand warmers to speed up the process of rewarming their hands between tasks. As the hand temperatures of HCWs can vary substantially in real-life scenarios, future studies need to investigate the effects of hand temperature on system performance.

This study was conducted in a laboratory setting, where the room temperature was controlled and did not vary substantially. However, room temperature could affect the temperature of the alcohol-based formulation and its evaporation rate, impacting the performance of the system. The laboratory's ambient temperature was set at a standard temperature (i.e. 21–24 °C), as defined by the Guidelines for Construction and Equipment of Hospital and Medical Facilities [31]. However, future studies are needed to examine its performance and applicability in real healthcare settings.

Finally, the alcohol-based formulation itself was a limitation. In this study, a coloured antimicrobial hand gel (Microshield Angel Blue, Schülke & Mayr GmbH) was mixed with a fluorescent hand rub formulation (Glitterbug Gel, OnSolution Pty Ltd), and both gels had been used in prior research or were implemented in healthcare settings [32–35]. Correlation between the type of alcohol-based formulation and performance of the system should be explored further. Different types of alcohol-based formulation may have different sterilization efficiencies, which may result in insufficient disinfection of the areas covered by alcohol-based formulation. Thus, alcohol-based formulations used in future studies should meet EN 1500 and ASTM E-1174 standards to ensure their sterilization efficiency [2].

In conclusion, this study showed the feasibility of using thermal imaging to detect hand coverage with alcohol-based formulation, thereby monitoring the quality of hand hygiene. In an evaluation with 32 participants, the system achieved promising results in terms of accuracy and Dice coefficient, while being comparable to the gold standard for UV concentrate. This study shows the potential flexibility of using thermal imaging to monitor the quality of hand hygiene, which can be a step towards a continuous automated hand hygiene monitoring system that allows real-time monitoring without interrupting the daily routines of HCWs.

Conflict of interest statement
None declared.

Funding sources
This work was funded, in part, by NHMRC Grants 1170937 and 2004316, the European Union's Horizon 2020 research and innovation programme (Grant No. 957296), and PhD Write Up Award from the Faculty of Engineering and Information Technology, University of Melbourne, Australia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhin.2023.05.016.

References

[1] Allegranzi B, Pittet D. Role of hand hygiene in healthcare-associated infection prevention. J Hosp Infect 2009;73:305–15.
[2] World Health Organization. WHO guidelines on hand hygiene in health care. Geneva: WHO; 2009.
[3] Pittet D. Improving adherence to hand hygiene practice: a multidisciplinary approach. Emerg Infect Dis 2001;7:234–40.
[4] Stefl ME. To err is human: building a safer health system in 1999. Front Health Serv Manage 2001;18:1–2.
[5] Klevens RM, Edwards JR, Richards CL, Horan TC, Gaynes RP, Pollock DA, et al. Estimating health care-associated infections and deaths in U.S. hospitals, 2002. Public Health Rep 2007; 122:160–6.
[6] De Angelis G, Murthy A, Beyersmann J, Harbarth S. Estimating the impact of healthcare-associated infections on length of stay and costs. Clin Microbiol Infect 2010;16:1729–35.
[7] Korhonen A, Ojanpera H, Puhto T, Jarvinen R, Kejonen P, Holopainen A. Adherence to hand hygiene guidelines – significance of measuring fidelity. J Clin Nurs 2015;24:3197–205.
[8] Arias AV, Garcell HG, Ochoa YR, Arias KF, Miranda FR. Assessment of hand hygiene techniques using the World Health Organization's six steps. J Infect Public Health 2016;9:366–9.
[9] Szilagyi L, Haidegger T, Lehotsky A, Nagy M, Csonka E-A, Sun X, et al. A large-scale assessment of hand hygiene quality and the effectiveness of the "WHO 6-steps". BMC Infect Dis 2013;13:249.

[10] Wang C, Jiang W, Yang K, Yu D, Newn J, Sarsenbayeva Z, et al. Electronic monitoring systems for hand hygiene: systematic review of technology. J Med Internet Res 2021;23:e27880.

[11] Boyce JM. Hand hygiene compliance monitoring: current perspectives from the USA. J Hosp Infect 2008;70:2–7.

[12] Goroncy-Bermes P, Koburger T, Meyer B. Impact of the amount of hand rub applied in hygienic hand disinfection on the reduction of microbial counts on hands. J Hosp Infect 2010;74:212–8.

[13] Llorca DF, Parra I, Sotelo MA, Lacey G. A vision-based system for automatic hand washing quality assessment. Mach Vis Appl 2011;22:219–34.

[14] Hoey J, Poupart P, Bertoldi A v, Craig T, Boutilier C, Mihailidis A. Automated handwashing assistance for persons with dementia using video and a partially observable Markov decision process. Comput Vis Image Understand 2010;114:503–19.

[15] Wang C, Sarsenbayeva Z, Chen X, Dingler T, Goncalves J, Kostakos V. Accurate measurement of handwash quality using sensor armbands: instrument validation study. JMIR Mhealth Uhealth 2020;8:e17001.

[16] Kutafina E, Laukamp D, Bettermann R, Schroeder U, Jonas SM. Wearable sensors for elearning of manual tasks: using forearm EMG in hand hygiene training. Sensors 2016;16:1221.

[17] Li H, Chawla S, Li R, Jain S, Abowd GD, Starner T, et al. Wristwash: towards automatic handwashing assessment using a wrist-worn device. In: ISWC '18: Proceedings of the 2018 ACM International Symposium on Wearable Computers; 2018. p. 132–9.

[18] Wang C, Jiang W, Yang K, Sarsenbayeva Z, Tag B, Dingler T, et al. A system for computational assessment of hand hygiene techniques. J Med Syst 2022;46:36.

[19] Wang C, Yang K, Jiang W, Wei J, Sarsenbayeva Z, Goncalves J, et al. Hand hygiene quality assessment using image-to-image translation. In: Medical Image Computing and Computer Assisted Intervention 2022: 25th International Conference; 18–22 September 2022, Singapore, p. 64–73.

[20] Bernard V, Staffa E, Mornstein V, Bourek A. Infrared camera assessment of skin surface temperature – effect of emissivity. Phys Med 2013;29:583–91.

[21] Boyce JM, Martinello RA. Pilot study of using thermal imaging to assess hand hygiene technique. Am J Infect Control 2022; 50:1208–11.

[22] Smieschek M, Stollenwerk A, Jüptner P, Kowalewski S, Orlikowsky T, Schoberer M. Evaluating hand disinfection with alcohol-based hand sanitizers using thermal imaging. CEUR Workshop Proceedings; 2016.

[23] World Health Organization. How to handrub with alcohol-based formulation. Geneva: WHO; 2015.

[24] Oerlemans HM, Graff MJ, Dijkstra-Hekkink JB, De Boo T, Goris RJA, Oostendorp RA. Reliability and normal values for measuring the skin temperature of the hand with an infrared tympanic thermometer: a pilot study. J Hand Ther 1999; 12:284–90.

[25] Taghanaki SA, Zheng Y, Zhou SK, Georgescu B, Sharma P, Xu D, et al. Combo loss: handling input and output imbalance in multi-organ segmentation. Comput Med Imag Graphics 2019;75:24–33.

[26] Lehotsky A, Szilagyi L, Bansaghi S, Szeremy P, Weber G, Haidegger T. Towards objective hand hygiene technique assessment: validation of the ultraviolet-dye-based hand-rubbing quality assessment procedure. J Hosp Infect 2017;97:26–9.

[27] Welch PD. The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. IEEE Trans Audio Electroacoust 1967; 15:70–3.

[28] Boyce JM, Pittet D. Guideline for hand hygiene in health-care settings: recommendations of the Healthcare Infection Control Practices Advisory Committee and the HICPAC/SHEA/APIC/IDSA Hand Hygiene Task Force. MMWR Recomm Rep 2002;51:1–45, quiz CE1–4.

[29] Smieschek M, Kobsik G, Stollenwerk A, Kowalewski S, Orlikowsky T, Schoberer M. Aided hand detection in thermal imaging using RGB stereo vision. In: Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society; 2019.

[30] Lugaresi C, Tang J, Nash H, McClanahan C, Uboweja E, Hays M, et al. MediaPipe: a framework for building perception pipelines. ArXiv 2019:abs/1906.08172.

[31] US Department of Health and Human Services. Guideline for construction and equipment of hospital and medical facilities. Washington: Government Printing Office; 1984.

[32] Repanovici A, Cotoros D, Haineala M, Nemet C, Dinu E. Systems for monitoring hands hygiene of medical staff in hospitals. 2020 8th E-Health and Bioengineering Conference; 2020.

[33] Andonian J, Galusha KE, Maragakis LL, Garibaldi BT. The impact of high-level isolation units beyond high-consequence pathogen preparedness. Health Secur 2019;17:69–73.

[34] O'Donoghue M, Ho JM, Pittet D, Suen LK. Acceptability and tolerability of alcohol-based hand hygiene products for elderly residents in long-term care: a crossover study. Antimicrob Resist Infect Control 2019;8:165.

[35] Lindsay HA, Hannam JA, Bradfield CN, Mitchell SJ. Breath alcohol of anesthesiologists using alcohol hand gel and the "five moments for hand hygiene" in routine practice. Can J Anaesth 2016; 63:938–44.