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To cite this article: Juyeon Park (2022) The role of base-layer cooling conditions in human error occurrences during doffing of personal protective equipment in health care, International Journal of Occupational Safety and Ergonomics, 28:2, 1016-1024, DOI: [10.1080/10803548.2020.1858611](https://doi.org/10.1080/10803548.2020.1858611)

To link to this article: <https://doi.org/10.1080/10803548.2020.1858611>



Published online: 20 Jan 2021.



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The role of base-layer cooling conditions in human error occurrences during doffing of personal protective equipment in health care

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This study compared error rates during the personal protective equipment (PPE) removal process under different base-layer cooling conditions while performing the doffing procedures. Ten participants were recruited and received training on the standard doffing procedures before participating in the experiments. The participants were randomly assigned to one of the three base-layer conditions and ran on a treadmill for 30 min. Their physiological biometrics were monitored during exercise trials, and error rates were calculated. The results revealed a significant difference in error rates when PPE was worn over base-layer scrubs made of a cooling fabric versus when it was worn over the conventional medical scrubs. Further, there was a strong negative relationship between the body coverage amount with the cooling fabric and error rates occurring during the doffing procedures. Findings suggested practical considerations for the operational monitoring system and improved PPE design to avoid unintentional errors during the doffing procedures.

Keywords: personal protective equipment (PPE); doffing procedures; error analysis; cooling fabric; base layer; health care

1. Introduction

Infectious disease transmission in healthcare workers (HCWs) tends to occur even if they are fully covered using personal protective equipment (PPE). A World Health Organization report on Ebola in Western Africa [1] showed that HCWs were at higher risk of infectious disease transmission than the general public by as much as 32 times. Due to the alarming report on HCWs' safety, the Centers for Disease Control and Prevention [2] updated its guidelines and specified procedural details for donning and doffing of PPE, along with multimedia training instructions to be used in the healthcare field. A complete set of medical PPE, which is recommended in the revised CDC guidelines, consists of an isolation gown or coverall, head covering, gloves, face shield, mask and shoe covers. To ensure protection from the spread of high-risk infectious diseases, the isolation gown must be made of an impermeable non-woven material to meet the required standard for PB70 Level 4 by the American National Standards Institute/Association of the Advancement of Medical Instrumentation (ANSI/AAMI).

However, whereas complete coverage and imperviousness to fluid are critical for infection prevention, a favorable wearing environment is another critical consideration for PPE design. If the need for wearability is not satisfied, an extremely uncomfortable physical environment for HCWs is likely to occur, especially when protective clothing is worn in a hot and humid climate such as sub-Saharan

Africa. That is, the overheated inner-PPE environment, due to the impermeable materials, puts HCWs in a vulnerable condition of virus infection by accidentally wiping their face or rushing to take off gloves during the doffing procedures of contaminated PPE, which can create significant physiological and physical stress to the wearers. The procedural risk factor was validated in previous studies [3,4], with most problems or incorrect practices being related to doffing sequences under various PPE wearing protocols. Moreover, heat stress is considered one of the substantial stresses imposed on occupational workers resulting from wearing PPE [5]. Heat stress also limits working duration and reduces cognitive functioning of occupational workers [6,7]. The adverse outcomes from the use of PPE have led to research efforts in defining a better wearing environment for HCWs by introducing personal cooling to the PPE, and the effectiveness has been confirmed [8].

As already described, human error occurs when people are asked to work in an environment in which great precision is required [9]. Sharit [10] defined two representative scenario cases of human error in occupational contexts. The first case describes workers who perform a task in a restricted space or condition; and the other case involves workers, particularly skilled workers, who adapt to the work environment that has rigid and unrealistic requirements. He explained that the worker's action in the first case tends to result in an unintentional accident, while the latter case involves an intentional action that leads to

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human error. He classified the occupational environment resulting from the use of PPE as an unintentional adverse work scenario. Applying the definition of human error, an infectious transmission during patient care while wearing the required PPE is considered an unintentional consequence, given that the work environment for HCWs is physically restricted and unbearable; and the consequences of those errors are lethal, often life-threatening.

In this study, we evaluated the effect of the PPE wearing environment on human errors occurring during the doffing procedures. Specifically, we compared error rates during the PPE removal process under the different base-layer cooling conditions while performing the CDC-recommended doffing procedures [2]. We formulated the following four hypotheses to guide this study. The first two hypotheses (H_1 and H_2) were developed to objectively gauge the effect of the different base-layer cooling conditions on physiological heat stress, thus confirming the ranking of base-layer conditions by favorable wearability as follows:

H_1 : There is a significant change in physiological heat stress when PPE is worn over base-layer scrubs made of a cooling fabric, relative to the conventional inner-PPE environment with no cooling.

H_2 : There is a strong negative relationship between the body coverage amount with a cooling fabric and physiological heat stress while wearing PPE.

Further, the following hypotheses (H_3 and H_4) were developed to predict the relationships between the base-layer cooling conditions and human error occurrences during the CDC-recommended doffing procedures:

H_3 : There is a significant change in human error occurrences when PPE is worn over base-layer scrubs made of a cooling fabric, relative to the conventional inner-PPE environment with no cooling.

H_4 : There is a strong negative relationship between the body coverage amount with a cooling fabric and human error occurrences during the PPE doffing procedures.

2. Methods

2.1. Participants

Ten participants, including five males and five females, were recruited through the emailing system of a 4-year public university located in the western region of the USA. The inclusion criteria for the participants were those who were aged 18 years and older, fit into medium-sized clothes, had no history of musculoskeletal or diabetic problems and were willing to participate in this research project. The particular clothes size was considered in the inclusion criteria to limit the variability of PPE size among the study participants. Further, to control the variance of the participants by gender, we adopted a matched-sampling strategy that was guided by Stuart and Rubin [11]. First, we sent out an e-blast recruitment to potential participants through the

participating university's emailing system and collected email responses from interested people. We then screened their eligibility based on the aforementioned inclusion criteria, and matched samples by pairing up with one male participant and one female participant who were similar in age and body mass index (BMI).







The average age of all participants ($N = 10$) was 22.2 years (SD 3.3). The average height was 172.7 cm (SD 3.1) and the average weight was 69.0 kg (SD 17.7). The average age of the male participants was 22.8 years (SD 2.1) and that of the female participants was 21.6 years (SD 1.3). The average height of the male participants was 177.8 cm (SD 1.1) and their average weight was 71.9 kg (SD 18.7), which made the average BMI for the males 22.7 (SD 2.3). For the female participants, the average height was 167.6 cm (SD 2.2) and the average weight was 66.0 kg (SD 15.8), which made the average BMI for the females 23.5 (SD 1.9). The average age and BMI for the male and female participants did not show a statistically significant difference ($p < 0.050$).

2.2. Procedures

For this study, the participants visited the research laboratory four times for a familiarization session and three exercise trials. During their first familiarization session, they were given an overview of the project scope and experiment procedures, and were invited to review the consent approved by the Institutional Review Board (IRB) of the participating university (ID 16-6965H). Once they agreed to participate in the study by signing the consent form, they were asked to fill out a short demographic survey. They were then shown a training video explaining the step-by-step donning and doffing procedures of the PPE [12], developed by Srinivasan et al. in collaboration with Medscape and the CDC, which was shown on a large television screen located in the laboratory. After watching the training video, the participants were allowed to ask any questions about the PPE donning and doffing procedures. Additionally, a researcher demonstrated the donning and doffing steps using a complete set of actual Level 4 PPE items and allowed the participants to practice the procedures with them as long as they wanted. With the specific focus of this study on PPE doffing only (not donning), we developed a written training manual containing a detailed description of the 22-step doffing procedure shown on the video and shared it with the participants as a study guide for their mastery of the doffing procedures after the laboratory training. Each participant was given 3 days or more to study the training manuals (e.g., the video link and the written manual) to comprehend the CDC-recommended PPE doffing procedures, to be prepared for the following experiments.

During the subsequent laboratory visit, to measure the effect of the inner-PPE environment on error occurrences,

Table 1. PPE wearing combinations.

Condition	PPE Wearing Combination		
	Base Layer	Outer Layer	Accessory
Control	Conventional medical scrubs	Level 4 surgical gown	Double gloves (two layers of gloves), facial shield, mask, head cover, shoe covers
			
EC1	Short-sleeve prototype top and scrub pants	Level 4 surgical gown	Double gloves (two layers of gloves), facial shield, mask, head cover, shoe covers
			
EC2	Long-sleeve prototype top and scrub pants	Level 4 surgical gown	Double gloves (two layers of gloves), facial shield, mask, head cover, shoe covers
			

Note: EC1 = experimental condition 1; EC2 = experimental condition 2; PPE = personal protective equipment

the participants were compared by the error rates occurring during the doffing procedures, under the three different base-layer scrub conditions that were worn under the Level 4 PPE. The different base-layer cooling conditions were set up by the following scrub combinations: (a) a top and a bottom set of conventional medical scrubs made of a 60/40 polyester/cotton blend as typically worn by HCWs in patient care (control); (b) a short-sleeved prototype scrub top made of a selected cooling fabric and a pair of the same scrub pants as the control (experimental condition 1 [EC1]); (c) a long-sleeved prototype scrub top made of the same selected cooling fabric as condition 2 and a pair of the same scrub pants as the control (experimental condition 2 [EC2]). Table 1 presents a visual reference of the PPE wearing combinations. The test cooling fabric was chosen based on the previous finding from our pilot study [13] that exhibited the highest cooling performance in human subjects, out of the currently available cooling fabrics on the

market. The core cooling mechanism of the selected fabric was crushed volcanic rock, and was characterized as a jersey knit (89% polyester and 11% elastane) weighing 175 g/m^2 . While the first inner-PPE environment represented the current standard practice for PPE by HCWs as a control case, the second and third experimental conditions (EC1 and EC2) demonstrated relatively favorable inner-PPE environments with integration of the cooling fabric. For the variance of body coverage, we tested the hypotheses with a focus on the sleeve length of the scrub top because our pilot data identified that the upper torso was the most heated body area while wearing PPE, indicated by physiological biometric measures (heart rate [HR], breathing rate [BR] and skin temperature [T_{sk}]) as well as the qualitative narratives that pointed out a perspiration issue on the lower arms due to the outer-layer PPE directly touching the skin, which was exposed by wearing the conventional short-sleeved scrub top. In evaluating the effect

Table 2. Physiological biometrics during exercise at baseline.

Biometric		Adaptation(5 min)	Rise(10 min)	Peak(10 min)	Finish(5 min)	Recovery(10 min)
HR (bpm)	Overall	104.2 ± 9.6	138.9 ± 10.7	162.6 ± 4.5	157.7 ± 11.4	134.4 ± 4.6
	Male	100.8 ± 8.7	132.2 ± 10.1	156.3 ± 4.8	153.3 ± 10.1	133.8 ± 3.6
	Female	107.5 ± 10.6	145.6 ± 11.4	168.8 ± 4.9	162.0 ± 12.7	135.1 ± 6.8
BR (bpm)	Overall	21.3 ± 2.4	27.8 ± 2.4	34.3 ± 1.3	33.7 ± 3.3	19.7 ± 2.0
	Male	20.7 ± 2.8	26.0 ± 1.8	31.4 ± 1.3	30.8 ± 3.0	16.7 ± 2.3
	Female	21.8 ± 1.2	29.7 ± 3.2	37.3 ± 1.5	36.6 ± 3.7	22.8 ± 1.7
T_{sk} (°C)	Overall	35.6 ± 0.2	36.8 ± 0.4	37.8 ± 0.3	38.4 ± 0.0	38.2 ± 0.2
	Male	35.9 ± 0.1	36.6 ± 0.3	37.4 ± 0.2	37.9 ± 0.0	37.9 ± 0.0
	Female	35.3 ± 0.3	36.9 ± 0.5	38.3 ± 0.3	38.8 ± 0.1	38.5 ± 0.4
GSR (μ s)	Overall	10.7 ± 0.9	17.5 ± 3.7	34.6 ± 7.6	49.3 ± 7.4	29.4 ± 2.8
	Male	11.5 ± 0.9	19.4 ± 4.1	39.3 ± 12.1	61.1 ± 15.4	36.2 ± 3.2
	Female	9.9 ± 0.9	15.7 ± 3.5	29.8 ± 4.0	37.4 ± 2.7	21.2 ± 2.1

Note: BR = breathing rate; GSR = galvanic skin response; HR = heart rate; T_{sk} = skin temperature.

of body coverage with the cooling fabric on error rates, we focused on one design variation, i.e., sleeve length, in this study to control for confounding variables.

For the comparison of error occurrences resulting from the different inner-PPE environments, the participants participated in a treadmill exercise under each of the base-layer cooling conditions along with a full set of Level 4 PPE. In order to avoid bias due to the participant's physical fatigue and the learning effect, we performed only one exercise on a given day with a minimum 24-h interval between the exercises, and we randomly assigned an inner-PPE wearing option to a participant on a given test day. For each exercise trial, the participants were asked to put on an assigned set of PPE and walk on a treadmill at 8 km/h for 30 min with 10 min of recovery (a total of 40 min). To monitor a participant's physiological responses, we used a wearable sensor vest (Equival[®] Life Monitor, UK) and put the device as the innermost layer against the participant's chest skin under the PPE. After the treadmill exercise, the participant was asked to remove all PPE items, following the CDC doffing procedures. At least one researcher was present in the same room as the participant to offer assistance if/when needed and to document the procedures using ethnographic field notes based on direct observation of the doffing practices; however, she/he was not allowed to correct errors directly for the participant. All practices of PPE doffing were video-recorded, and the data were used for error rate calculation and further verification of data accuracy through iterative examination.

2.3. Data analysis

SPSS version 25.0 was used for statistical analyses. Descriptive statistics obtained from physiological biometric data and error rate analysis calculated means, standard deviations and percentages. Repeated-measures analysis of variance (ANOVA) tests with the Greenhouse–Geisser

correction were performed at $p < 0.050$ to compare mean differences of error rates across the base-layer cooling conditions. For the comparison of error rates between EC1 and EC2, we used a one-sample t test (Kolmogorov–Smirnov test) rather than a paired-samples t test, because we were interested in comparisons of the overall frequency of errors during the doffing procedures between the base-layer cooling conditions instead of the before and after data comparison at each doffing task step. We also gained insights from the observers' ethnographic field notes. We used tables and graphic charts to organize the data. All data sets were compared and contributed to the conclusion of the results through data triangulation.

3. Results

3.1. Physiological heat stress

To gauge the heat stress experienced by the study participants in the baseline (control) condition, we monitored their physiological biometrics in real time during the moderate-intensity physical activity through the treadmill exercise and recovery, with participants wearing the standard Level 4 PPE with the conventional medical scrubs underneath. Table 2 summarizes the average HR, BR, T_{sk} and galvanic skin response (GSR) within the five exercise-recovery phases, in the context of the standard PPE condition. Overall, the physiological biometric data indicated an increase over the 30-min treadmill exercise phases and a decrease during the 10-min recovery phase. The mean HR at the adaptation phase (for the first 5 min of the exercise) was 104.2 bpm (SD 9.6) and reached 162.6 bpm (SD 4.5) during the peak exercise phase. Similarly, the mean BR started at 21.3 bpm (SD 2.4) and increased as high as 34.3 bpm (SD 1.3). On average, the mean T_{sk} changed by as much as 2.8 °C from 35.6 to 38.4 °C during the exercise. The GSR also showed a trend consistent with the other biometrics, with a dynamic increase during the exercise and a decrease at the recovery. That is, the mean GSR during the

Table 3. Comparison of heat stress indicators by inner-PPE environments.

Biometric	Inner-PPE environment			<i>F</i>	<i>df</i>	<i>p</i>
	Control	EC1	EC2			
HR (bpm)	142.8 ± 21.1	137.6 ± 20.4	132.3 ± 19.2	281.991	1.547	0.000
BR (bpm)	28.5 ± 1.1	28.3 ± 5.7	28.0 ± 5.7	10.536	1.805	0.000
T_{sk} (°C)	37.3 ± 1.0	36.9 ± 1.1	36.8 ± 1.1	934.440	1.701	0.000
GSR (μ s)	27.2 ± 14.4	22.8 ± 13.2	20.4 ± 12.0	3752.463	1.613	0.000

Note: BR = breathing rate; EC1 = experimental condition 1; EC2 = experimental condition 2; GSR = galvanic skin response; HR = heart rate; PPE = personal protective equipment; T_{sk} = skin temperature.

adaptation phase was 10.7 μ s (*SD* 0.9) and increased up to 49.3 μ s (*SD* 7.4), which showed the heat stress level that the participants experienced based on electrodermal skin conductivity.

In order to verify the levels of heat stress experienced during the treadmill exercise under the three different base-layer cooling conditions (1 control + 2 experimental conditions), we compared mean biometrics in participants across the three conditions (Table 3). Overall, the physiological biometric data decreased from the control condition to EC1 (short-sleeved scrub) and further to EC2 (long-sleeved scrub). That is, the cooling PPE conditions showed generally improved heat stress indicators in all biometrics measured, relative to the control condition. Thus, H_1 was supported.

Further, the data for EC2 indicated more favorable results in the measures of heat stress than those for EC1. To elaborate, overall the heat stress measured through the HR, BR, T_{sk} and GSR was diminished when PPE was worn with the short-sleeved scrub top (EC1), compared to the control condition, and it was further decreased from the EC1 levels when wearing the long-sleeved scrub top (EC2) under PPE. The results of the repeated-measures ANOVA with the Greenhouse–Geisser correction confirmed strong differences in the mean scores in each of the physiological biometrics (95% confidence interval). That is, a larger area of body coverage with the cooling fabric – specifically the lower arms in this case – significantly helped reduce the heat stress the participants experienced while wearing PPE. Therefore, H_2 was supported.

3.2. Error rates during PPE doffing

To assess the role of base-layer cooling conditions on human error occurrences, we examined the error frequency during the standard PPE doffing procedures recommended by the CDC [12]. The average score for all participants was 18.2 out of 22 possible doffing steps (82.7% of correct steps; *SD* 2.7), ranging from 68.1 to 95.5% (15–21 correct steps, respectively). There was no mean difference in the test scores by gender (males 82.8%, *SD* 5.9; females 82.8%, *SD* 12.6), demonstrating that the baseline knowledge of the doffing procedures was not different between

male and female participants (95% confidence interval). Further, we examined 102 total errors made by the study participants to investigate the specific task steps in which errors frequently occurred during the PPE doffing procedures. The results (Table 4) showed that the procedural errors occurred most frequently during the glove removing steps (60% error rate for step 6 and 50% error rate for step 7). Specifically, the participants often switched the orders between step 6 and step 7. That is, participants recurrently disinfected contaminated inner gloves using hand hygiene before inspecting the gloves for cuts and tears. In this case, we marked both steps 6 and 7 as incorrect.

Another interesting finding was that the participants tended to make errors at the beginning and toward the end of the sequential doffing procedures. As highlighted in Table 4, the relatively higher error occurrences were reported at the beginning and at the end of the procedures than during the mid-phase. For example, the participants frequently forgot to perform the disinfection steps around the beginning and end of the procedures, while they more consistently remembered the similar steps during the mid-procedures. While all of the participants performed the correct doffing procedures at steps 8, 9, 12 and 13 (0% of error rate), more participants tended to make errors at the beginning and at the end – as noticed in steps 2 and 5 (40% error rate) during the beginning procedures and steps 18, 19, 21 and 22 (30, 40, 30 and 30% error rate, respectively) during the end procedures (refer to Table 4). This finding is critical to note, indicating that HCWs must be monitored with extra caution when they start performing the doffing procedures and when they are near the end of the procedures.

Additionally, we organized the errors occurring during the doffing procedures by commission versus omission errors and examined the modes of recovery actions performed in such error cases (Table 5). Largely, the commission error type was more frequently observed than the omission type during the early steps of the doffing procedures. Also, once a commission-type error happened, the participants tended to remember the correct step shortly after and tried to correct the sequence by redoing it. On the other hand, as the doffing sequence reached toward the end, the participants tended to forget the disinfection and

Table 4. Error rates by doffing task steps.

Period	Task	Procedure	Error rate (%) by task
1(beginning)	1	Wait until a trained observer is ready; inspect overall visible contamination, cuts or tears	30
	2	Disinfect outer pair of gloves using hand hygiene	40
	3	Have participant sit down on a chair for removing shoe covers; then remove the shoe covers	0
	4	Disinfect outer pair of gloves using hand hygiene	0
	5	Remove outer pair of gloves carefully	40
	6	Inspect inner gloves for cuts and tears	60
	7	Disinfect inner gloves using hand hygiene	50
2(middle)	8	Next, remove the face shield by pulling it forward over the head without touching the front the shield	0
	9	Disinfect gloves using hand hygiene	0
	10	Carefully remove the surgical hood by holding the back of the hood and carefully pulling it forward	10
	11	Disinfect gloves using hand hygiene	10
	12	Carefully remove gown by pulling the gown away from the body rolling it inside out, only touching the inside of the gown	0
	13	Disinfect gloves using hand hygiene	0
	14	Remove inner pair of gloves	10
3(end)	15	Perform hand hygiene on the bare hands; once dry, put on a fresh pair of nitrile gloves	10
	16	Next, remove N95 respirator	10
	17	Disinfect gloves using hand hygiene	10
	18	Sit on clean chair specifically for disinfecting shoes; use a wipe to disinfect shoes	30
	19	Disinfect gloves using hand hygiene	40
	20	Carefully remove gloves	0
	21	Disinfect bare hands using hand hygiene	30
	22	Do a final inspection for visual contamination	30

final check steps. Although they recalled the steps later in the task sequence, they were already at the end of the procedures so no recovery action was performed.

3.3. Comparison on error rates by base-layer cooling conditions

Next, we calculated the error rates across the base-layer cooling conditions. Descriptively, the average error rate of the doffing procedures under the control wearing condition was 18.6% (SD 18.8), whereas that of EC1 (with the short-sleeved scrub top) and EC2 (with the long-sleeved scrub top) was 15.5% (SD 18.2) and 14.1% (SD 16.2), respectively. To validate the statistical significance of the changing trend in error occurrences by the base-layer cooling conditions, we performed a repeated-measures ANOVA test, and the result determined that the differences in the error rates across the inner-PPE wearing conditions were statistically significant ($F = 20.264$, $df = 21$, mean square = 840.115, $p = 0.000$). That is, the average error rate was highest for the control case, followed by EC1 (when a short-sleeved scrub top was worn as a base layer) and then by EC2 (when a long-sleeved scrub top was worn underneath a full set of PPEs). Therefore, H_3 was supported.

Further, we evaluated how the variance of body coverage with the cooling fabric affected error rates occurring during the PPE doffing procedures. The result of the non-parametric one-sample t test (Kolmogorov–Smirnov test) evinced statistical significance for the relationship between the body coverage amount and human error occurrences, which tested H_4 . That is, the comparison of means for error rates between EC1 and EC2 was significant ($p = 0.000$) (Table 6), which signified that EC2 with higher body coverage (long-sleeved) offered the participants a relatively more favorable inner-PPE environment than EC1 (short-sleeved), as the lowest error rate indicated. Conversely, the higher error rate was observed when a short-sleeved scrub top was worn (EC1), compared to that of EC2. These findings supported H_4 .

4. Discussion

This study investigated how human errors occur under the different base-layer cooling conditions with the variance of body coverage during the PPE doffing procedures in health care. Specifically, we took a material approach to define the independent variable of body coverage by applying a particular test fabric with the effective cooling function as determined in our pilot effort. First, in order to verify the

Table 5. Type of errors and recovery actions.

Task	Task description	Error type	Error description	Recovery
1	Wait until a trained observer is ready; inspect overall visible contamination, cuts or tears	Omission	Skipped task	No recovery
		Commission	Either did not wait for a trained observer or did not perform inspection	Performed later in sequence
2	Disinfect outer pair of gloves using hand hygiene	Omission	Skipped task	Performed later in sequence
5	Remove outer pair of gloves carefully	Commission	Switched with adjacent steps	Tried to correct action by redoing
6	Inspect inner gloves for cuts and tears	Commission	Never got this task right Switched with adjacent steps	No recovery Tried to correct action by redoing
		Omission	Skipped task	Performed later in sequence
7	Disinfect inner gloves using hand hygiene	Commission	Switched with adjacent steps	Tried to correct action by redoing
15	Perform hand hygiene on the bare hands; once dry, put on a fresh pair of nitrile gloves	Commission	Switched with adjacent steps	Tried to correct action by redoing
18	Sit on clean chair specifically for disinfecting shoes; use a wipe to disinfect shoes	Omission	Skipped task	Performed later in sequence
		Commission	Switched with adjacent steps	Tried to correct action by redoing
19	Disinfect gloves using hand hygiene	Omission	Skipped task	Performed later in sequence
		Commission	Switched with adjacent steps	Tried to correct action by redoing
21	Disinfect bare hands using hand hygiene	Omission	Skipped task	No recovery
		Omission	Skipped task	No recovery
22	Do a final inspection for visual contamination	Omission	Skipped task	No recovery

Table 6. Result of the one-sample Kolmogorov–Smirnov test.

Variable		Inner-PPE environment	
		EC1 (<i>N</i> = 22)	EC2 (<i>N</i> = 22)
Normal parameter	Mean	15.45	14.55
	<i>SD</i>	18.19	17.38
Most extreme difference	Absolute	0.300	0.285
	Positive	0.300	0.285
	Negative	−0.198	−0.201
Test statistics	—	0.300	0.285
Asymptotic significance (2-tailed)	—	0.000	0.000

Note: EC1 = experimental condition 1; EC2 = experimental condition 2; PPE = personal protective equipment.

rank of favorable inner-PPE wearing environments among the three base-layer conditions (control vs EC1 vs EC2), we quantified physiological heat stress experienced by the study participants under each of the three conditions based on the vital biometric indicators (HR, BR, T_{sk} , GSR) for thermal comfort. The results indicated that EC2 (PPE worn with a long-sleeved cooling scrub top) offered the most favorable inner-PPE wearing environment to the participants, followed by EC1 (PPE worn with a short-sleeved cooling scrub top) and then the control condition (PPE

worn with a conventional scrub top with no cooling). Upon confirmation of the rank in heat stress, we performed the doffing procedures to identify the relationship of the favorable inner-PPE wearing environment with the frequency of human errors occurring during the removal steps. The data revealed a negative association between the test variables, as unintentional human errors occurred least under EC2, followed by EC1 and then the control.

Additionally, the error analyses revealed some interesting findings that are worth noting. Based on 102 total

errors observed in this study, a higher error frequency was noticed at the beginning and at the end of the procedures than in the mid phase. Further, the errors made in the earlier phase of the doffing procedures were more likely to be commission errors, whereas those made toward the end of the procedures were characterized as omission errors. A commission error results from incorrectly remembering information, whereas an omission error occurs due to the failure to remember information to which one has been exposed [14]. Fundamentally, Reason [15] explained that when the appropriate action is carried out incorrectly, the error is classified as a slip and when the action is simply omitted or not carried out, the error is termed a lapse. That is, he claimed that a slip (an error of commission) is a failure of memory and a lapse (an error of omission) is a failure of attention. Applying this concept to the present research data, commission errors, which frequently occurred in the earlier phase of the doffing procedures, were due to forgetting correct procedures, and omission errors tended to occur toward the end of the doffing procedures and were caused by weakened attention. Further, fatigue or physical heat strain could adversely affect one's capabilities for information processing, thus resulting in limited working memory and loss of attention [16].

This study is subject to several limitations. Despite the aforementioned practical findings, the hypotheses were tested in a laboratory setting with a small sample size. Moreover, in an effort to minimize the effect of individual variance among study participants, we adopted the matched-sampling strategy (for participant sampling) and repeated-measures mean comparison tests (for data analysis) in the within-subject study design (for research design). Although this approach reflects our careful measures in this matter, it will be still advisable to conduct future research with human subjects representing various physical and occupational backgrounds who characterize varying levels of individual metabolic costs, occupational exposures to infectious risks, and frequency and history of wearing PPE in their job settings. Further, to increase the generalizability of the data, it will be beneficial to verify the findings in a real occupational context with actual HCWs. Additionally, in this study, we only focused on the scrub top as a particular base layer to apply a selected cooling fabric and measured the effect of the independent variable (i.e., the body coverage amount with the cooling fabric) on the human error rates occurring during the PPE doffing procedures. It will be desirable to expand the scope of the inner-PPE test area to the entire scrub including the top and bottom, so as to identify specific body parts that are more sensitive to heat stress and that are, resultantly, more vulnerable to making errors during the doffing procedures.

5. Conclusion

Nevertheless, human factors analysis of the doffing process has highlighted opportunities for the enhanced design

of PPE that can offer HCWs a safer, more bearable occupational environment. The CDC has proposed guidelines for various aspects of PPE for HCWs, such as the sequence of donning and doffing, disposal of contaminated PPE, training on procedures, etc. While most of the CDC guidelines focus on the outer shell of PPE (i.e., a full ensemble of PPE consisting of the isolation gown, face shield, mask, gloves, boot covers, hair covers, etc.), little attention has been given to the base layer that is worn under the PPE. This study presented practical suggestions for the selection and design of the base layer to be worn with the required PPE. On the other hand, the understandings gained from the error analyses highlight the need for an effective monitoring system, such as the buddy system that the CDC proposed, to provide HCWs with real-time reminders and feedback concerning the correct doffing procedures. Along the same vein, Gurses et al. [17] specified necessary knowledge, skills and attitudes for safer doffing of PPE, beyond the technical instructions for how to remove items of PPE. We hope the findings of this study will offer health-care administration and PPE manufacturing communities useful insights into improving the HCWs' occupational environment safety and health.

Acknowledgements

The author would like to recognize the students – Tyler Klene, Brittany Conroy, Varehya Pratt and Rachel Crain – who aided data collection with study participants.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported in part by Centers of Disease Control and Prevention/National Institute of Occupational Health and Safety (CDC/NIOSH), Mountain and Plains Education Research (MAP ERC) Pilot [grant number ID 5301312]; National Institute for Occupational Safety and Health .

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