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Review Article

Heat stress intervention research in construction: gaps and recommendations

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Abstract: Developing heat stress interventions for construction workers has received mounting concerns in recent years. However, limited efforts have been exerted to elaborate the rationale, methodology, and practicality of heat stress intervention in the construction industry. This study aims to review previous heat stress intervention research in construction, to identify the major research gaps in methodological issues, and to offer detailed recommendations for future studies. A total of 35 peer-reviewed journal papers have been identified to develop administrative, environmental or personal engineering interventions to safeguard construction workers. It was found that methodological limitations, such as arbitrary sampling methods and unreliable instruments, could be the major obstacle in undertaking heat stress intervention research. To bridge the identified research gaps, this study then refined a research framework for conducting heat stress intervention studies in the construction industry. The proposed research strategy provides researchers and practitioners with fresh insights into expanding multidisciplinary research areas and solving practical problems in the management of heat stress. The proposed research framework may foster the development of heat stress intervention research in construction, which further aids researchers, practitioners, and policymakers in formulating proper intervention strategies.

Key words: Intervention, Heat stress, Construction workers, Research framework, 5-D model

Introduction

Construction workers are susceptible to heat stress because of hot weather, highly demanding physical work, and prolonged exposure to direct sunlight[1]. Heat stress prevention is a pressing issue for researchers and practitioners, particularly because of the alarming number of heat-related casualties[2] and the corresponding financial and legal issues[3]. From both the moral and economic perspectives[4], controlling heat stress may offer multiple benefits, including decreased accidents and morbidity rates, improved productivity, and improved sense of social well-being[5].

A series of controlling measures has been promulgated and implemented in the construction industry to safeguard workers laboring in hot weather. Most existing precautionary guidelines adopt recognized international standards[6] as action-triggering benchmarks[7]. However, these guidelines are by and large *dos and don'ts* actions[8] and are believed to be over-conservative and lacking of validity under varying geographical, cultural, and socioeconomic contexts; hence, the risks posed by excessive heat exposure may be underestimated[7, 9, 10]. The re-engineering and implementation of effective intervention strategies with a robust scientific basis are thus important in managing heat stress risk in construction[7].

The need of intervention studies has been increasingly recognized in the field of occupational health over the past three decades[11, 12]. Intervention study is a type of research that allows conclusions on the cause-effect relationship

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mediated by intervention[13]. The general aim of occupational intervention research is to improve the well-being and productivity of workers by reducing primary safety and health risks[12, 14, 15]. To formulate effective and practical guidelines, intervention research should be conducted to enable researchers, practitioners, and policymakers to develop, evaluate, and deliver proper interventions for target populations[16].

Intervention research has been widely employed in applied disciplines, such as occupational epidemiology, psychology and behavioral science, clinical medicine, and social science[17–20]. However, it rarely focuses on the construction industry largely because this industry is complex and characterized by diffused control, small employer firms, temporary work sites, multi-employer worksites, temporary employment, and numerous crafts[14]. The aim of the current study was to review previous heat stress intervention research in construction, to identify the major research gaps in methodological issues, and to offer detailed recommendations for future studies.

Methods

Selection of data sources

A three-step literature review was performed to identify heat stress intervention research in the construction industry and further to offer a content analysis of these studies. First, a comprehensive desktop search was conducted under the "title/abstract/keyword" field of the following prevalent multi-disciplinary databases: Springer, Scopus, Science Direct, EBSCOhost, IEEE Xplore, MedLine, Web of Science, Wiley Online Library, Taylor and Francis Online. Search keywords including heat/thermal stress and construction industry were used to find the potential publications. Research articles published in peer-reviewed journals between 1980 and October 2016 were retrieved. Commentaries, editorials, discussion letter, reviews, reports, and unpublished working papers were excluded, along with papers written in languages other than English. Second, snowballing was then conducted using the retrieved citations to perform a new search based on the article's bibliography, authors' names, and the 'related articles' search option of the search engine[21]. Third, full-length papers and abstracts only meeting the following inclusion criteria were selected for the content analysis: 1) developing one or more heat stress controlling measures in the construction industry, and 2) adopting empirical research methodologies based on data systematically collected from experiments, surveys or observations and analyzed results via primary or secondary research efforts[22, 23].

Study classification

The selected studies were classified according to the categories of heat stress controls, namely, administrative, environmental engineering, and personal engineering controls[6, 24], which was useful for describing the general focus of intervention studies.

1. Administrative controls are the assigned or rescheduled work practices and policies, which aim to reduce the magnitude, duration, and/or frequency of worker exposure to risk factors, e.g., training and education, proper work-rest rotation.
2. Environmental engineering controls aim to mitigate or eliminate worker exposure to the hazardous environment, e.g., provision of shields or portable fans.
3. Personal engineering controls aim to offer personal protective equipment that can protect workers from the hostile environment, e.g., protective clothing.

Results

Overview of the included studies

There were 26 articles relevant to heat stress interventions in construction being archived from the nine search engines in the first step of literature review. Another nine papers were found through snowballing search. A total of 35 peer-reviewed papers met all inclusion criteria based on the selection process. The trends of these published journal papers by year, country (region) the study applied, and category are illustrated in Table 1. These studies were generally conducted at the site level rather than at the national and international levels and their scope was neither company- nor industry-wide. Seventeen (49%) of studies focused on facilitating administrative intervention controls in construction, while ten (29%) of studies made efforts in developing personal engineering controls. Several studies had proposed multiple strategies to safeguard construction workers working in hot weather[1, 25, 26]. Heat stress intervention studies in construction considerably emerged after the year of 2012. The Hong Kong construction industry was the most prevalent target for heat stress intervention research.

Discussion

Administrative controls

Current research mainly focused on developing and stipulating proper administrative interventions through

Table 1. Overview of the selected studies

Author(s)	Year	Research origin	Category	Intervention
Bates and Schneider [25]	2008	United Arab Emirates	Administrative	Fluid intake, Self-pacing
			Environmental engineering	TWL monitoring
Bates *et al.* [27]	2010	United Arab Emirates	Administrative	Fluid intake
Chan and Yang[34]	2016	Hong Kong SAR	Administrative	PeSI monitoring
Chan *et al.*[30]	2012a	Hong Kong SAR	Administrative	Optimal recovery time
Chan *et al.*[31]	2012b	Hong Kong SAR	Administrative	Optimal recovery time
Chan *et al.*[42]	2012	Hong Kong SAR	Environmental engineering	TWL monitoring
Chan *et al.*	2013	Hong Kong SAR	Personal engineering	Hybrid cooling vest; Cooling vest with frozen gel packs
Chan *et al.*[45]	2013	Hong Kong SAR	Personal engineering	Hybrid cooling vest; Cooling vest with frozen gel packs
Chan *et al.*[46]	2015	Hong Kong SAR	Personal engineering	Hybrid cooling vest; Cooling vest with frozen gel packs
Chan *et al.*[47]	2016	Hong Kong SAR	Personal engineering	Hybrid cooling vest
Chan *et al.*[48]	2016	Hong Kong SAR	Personal engineering	Hybrid cooling vest
Chan *et al.*[49]	2016	Hong Kong SAR	Personal engineering	Hybrid cooling vest; Cooling vest with frozen gel packs
Chan *et al.*[50]	2016	Hong Kong SAR	Personal engineering	Hybrid cooling vest
Chan *et al.*[51]	2015	Hong Kong SAR	Personal engineering	Work unifrom
Chan *et al.*[52]	2016	Hong Kong SAR	Personal engineering	Work unifrom
Chan *et al.*[53]	2016	Hong Kong SAR	Personal engineering	Work unifrom
Dehghan *et al.*[41]	2012	Iran	Environmental engineering	WBGT monitoring
Farshad *et al.*[40]	2014	Iran	Environmental engineering	TWL monitoring
Heus and Kistemaker[44]	1998	n.a.	Personal engineering	Work unifrom
Jia *et al.*[37]	2016	Hong Kong SAR	Administrative	Socio-ergonomic model
Miller and Bates[28]	2007a	Australia	Administrative	Fluid intake
Miller and Bates[39]	2007	Australia	Environmental engineering	TWL monitoring
Miller *et al.*[4]	2011	United Arab Emirates	Administrative	Self-pacing
Montazer *et al.*[29]	2013	Iran	Administrative	Fluid intake
Rowlinson and Jia[9]	2014	Hong Kong SAR	Administrative	Optimized work-rest regimen
Rowlinson and Jia[38]	2015	Hong Kong SAR	Administrative	Proactive and reactive behavioural intervention
Pérez-Alonso *et al.*[1]	2011	Spain	Administrative	Optimized work-rest regimes
			Environmental engineering	ESI monitoring
Yabuki *et al.*[35]	2013	Japan	Administrative	Heatstroke prevention system
Yang and Chan[33]	2015	Hong Kong SAR	Administrative	PeSI monitoring
Yang and Chan[55]	2016	Hong Kong SAR	Personal engineering	Work uniform
Yi and Chan[8]	2013	Hong Kong SAR	Administrative	Optimized work-rest schedule
Yi and Chan[26]	2014	Hong Kong SAR	Administrative	Heat tolerance time
			Environmental engineering	WBGT monitoring
Yi and Chan[32]	2014	Hong Kong SAR	Administrative	Optimal work pattern
Yi *et al.*[36]	2016	Hong Kong SAR	Administrative	Early-warning system
Yi *et al.*[54]	2016	Hong Kong SAR	Personal engineering	Work unifrom

Abbreviation: ESI: environmental stress index; PeSI: perceptual strain index; TWL: thermal work limit; WBGT: wet bulb globe temperature

improving work practices, such as rescheduling of work rotation, provision of drinking water, and monitoring human heat strain. Strategies for developing these interventions have been focused on the process of quantifying heat stress (causes) and strain (consequences). For instance, Bates and Schneider[25], Bates *et al.*[27], Miller and Bates[28], and Montazer *et al.*[29] investigated the hydration status of construction workers and advised that interventions are required to maintain adequate levels of hydration of workers under extreme heat stress conditions. Chan *et al.*[30, 31], Yi and Chan[8, 26, 32], Rowlinson and Jia[9], and Pérez-Alonso *et al.*[1] proposed work and/or recovery thresholds after examining body heat strain limits arising from multiple heat stressors (e.g., meteorology, work and individual characteristics) in the Hong Kong construction industry. Heat strain monitoring is recommended to safeguard construction workers under safe physiological thresholds[33, 34]. Self-paced work in the heat is also suggested to avoid excessive heat strain triggered by inordinate work pace[4, 25]. With the use of assistive technology, several early-warning systems have been devised to issue an alert on the basis of physiological thresholds and the corresponding intervention strategies[35, 36]. By identifying the institutional factors leading to heat illness incidents, recent studies focused more on eliminating behavioral risks in perspective of management infrastructure[37, 38]. Despite the remarkable development of administrative controls, it is somewhat unclear to what extent the effectiveness of these controls on reducing heat stress can be demonstrated.

Environmental engineering controls

Environmental heat stress monitoring has been widely documented for assessing heat stress level of construction workers[1, 26, 31, 39–42]. The Wet Bulb Globe Temperature (WBGT) and the Thermal Work Limit (TWL) are two of the most widely used environmental monitoring indices at construction sites. However, the limitations of using these environmental indicators have been recognized. The reliability of these indicators remains debatable under different environmental conditions, and their environmental threshold should be compatible with personal characteristics, such as work pace, hydration status, and acclimatization status[7, 43]. Thus, these environmental thresholds may be invalid because of the changes in the boundary thresholds. Limited efforts have been exerted to develop other types of environmental engineering strategies, such as provision of air fans and working under the shade, although industrial guidelines acknowledge the importance of adopting these measures. Sound scientific evidences that could ascertain the effectiveness of these measures in aiding workers to combat heat stress have not been well documented.

Personal engineering controls

Heus and Kistemaker[44] conducted human wear trials in the laboratory experiments to examine the efficacy of a new work uniform in reducing physiological and perceptual strain. Chan and his colleagues administered a series of field surveys to evaluate the acceptability and practicality of wearing personal cooling vests at construction sites[45–50]. A new work uniform designed for construction workers have been proved to be effective in easing heat strain and improving wearing comfort through a series of laboratory and field experiments and questionnaire surveys[51–55]. Despite these, the major challenges of these studies lied in that only limited garments were scrutinized.

Major research gaps

Little effort has been exerted to elaborate the rationale, methodology, and practicality of heat stress intervention strategies in the construction industry. Interests from the scientific community in studying heat stress intervention strategies have only awakened in recent years. This situation may delay the process to formulate solid and proper strategies to aid construction workers in combating heat stress in advance. Most studies might employ more of a "try it and see" strategy based on the experiences of researchers[56]. Limitations of the above studies can be identified, including unclear theoretical basis, deficient research methodologies, and difficulty in applying the outcomes to practice, even though Goldenhar and Schulte[11, 57] had underlined these problems two decades ago.

Randomized control trials (RCTs), particularly in the real-work settings, were not widely performed in previous studies, probably resulting in systematic bias. Besides, the use of quasi-experimental and non-experimental research designs, pose a major threat to the internal validity of the study[11]. A double-blind trial can reduce information bias from participants and investigators involved in a given experiment and avoids the placebo effect on the intervention group[12]. Nevertheless, few studies have employed the double-blind trial to determine the benefits of the interventions. Although blinding and the placebo effect may not be the core elements of RCTs[12], their possible implications on research findings cannot be ignored.

Arbitrary sampling plan was another limitation in the study designs of previous research. The two important sampling issues in intervention research are subject selection and sample size; the former indicates the generalizability of findings and selection bias, whereas the latter may affect desired outcomes[11]. University students were recruited as the subjects to perform the experimental trials in laboratory settings[33, 53, 54]. However, the difference in physics between university students and construction workers should be recognized and thus, the generalizability of their findings was questioned. The sample size in intervention research should be sufficient to detect a difference in the outcomes of intervention and control groups[11]. A large sample size may increase the accuracy of calculated statistics as close as possible to the true population estimate[58]. When sample size is limited because of research time, funding, or human resources, statistical power calculations should be conducted and reported to provide a clear idea of the magnitude of the effects[59]. However, population sampling was arbitrary without justification on its statistical or practical significance in most of previous studies.

The reliability and validity of measurement instruments is essential in occupational intervention research[11]. Calibrating instruments is a critical procedure to guarantee the inter-instrument reliability[60] and data accuracy. The method to calibrate the body core temperature introduced by Chan *et al.*[53] could become a good practice of using reliable and valid instruments. Despite this, the measurement instruments were used in most of studies without calibration and justification. For instance, using tympanic temperature to measure physiological strain of construction workers[9, 30, 31] has to be recognized as a potential risk when direct measurement of body core temperature seems to be impractical at workplace. In view of this, the design of the non-invasive devices to monitor body core temperature has received growing attention[61]. Furthermore, the application of the developed interventions was not well documented and thus, their benefits in reducing heat stress risks remian ambiguous. The lack of comprehensive research methodologies may be one of the major obstacles in conducting heat stress intervention research in the construction industry. Regarding these existing limitations in research methodologies on heat stress intervention studies, there is a pressing need to elucidate a well-structured research framework for future works.

Recommendations

In view of the aforementioned research gaps, this study then refined a research framework for conducting heat stress intervention studies in construction. The National Institute for Occupational Safety and Health has been actively developing a theoretical framework for occupational intervention research and providing practical guidance[15, 62]. This framework emphasizes the capability of a well-designed intervention study to integrate development, implementation, and effectiveness research and subsequently to establish a cycle of continuous improvement of an intervention[15].

In the development phase, intervention studies are necessary not only to examine the utility of interventions in producing desired effects but also to disseminate convincing evidence when implementing interventions in the workplace[11, 12, 63]. Hence, the authors concur with the premise of Camp[19] on the *efficacy–effectiveness–diffusion* process for conducting intervention studies. The efficacy of an intervention is the degree to which it causes an effect under ideal conditions, whereas the effectiveness of an intervention is the degree to which it causes an effect under realistic workplace conditions[64]. That is, the efficacy analyses are primarily centered on inquiries into the likelihood of individuals in a defined population to benefit from an intervention under tightly controlled conditions[19], while effectiveness analyses investigate the distribution and effect of an intervention employed in daily operations under uncontrolled real-world settings[65]. Even though the efficacy and effectiveness of an intervention are demonstrated, the successful implementation of such intervention in a large population may remain uncertain[19]. In this regard, the next step is to solicit a body of evidence that supports the feasibility and acceptability of an intervention for large numbers of practitioners[19].

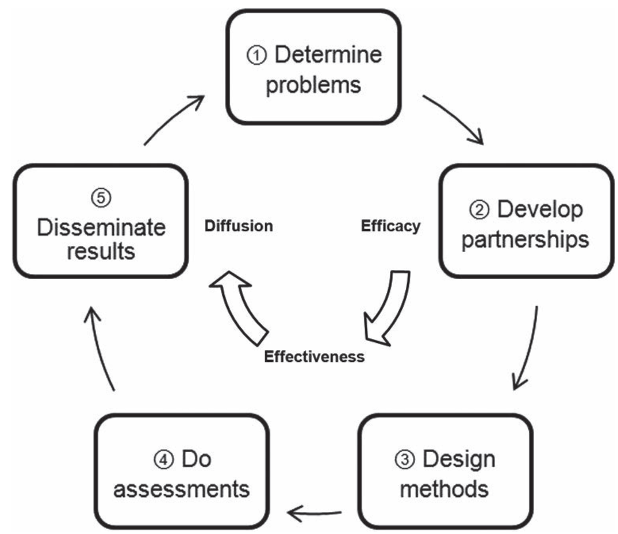

Fig. 1. The 5-D model for conducting intervention research.
Adapted from Goldenhar *et al.*[54], Robson *et al.*[55] and Camp[14].

This process is shown in an integrated 5-D model in Fig. 1 and in Table 2. This research framework combines the multidisciplinary perspectives of occupational safety and health and clinical medicine[15, 19, 62], which may provide a new perspective for the conduct of comprehensive intervention research. The proposed framework emphasizes the need to prove the efficacy, effectiveness, and diffusion of an intervention in the development research phase before such intervention undergoes the implementation and impact research phases for large populations.

Background information is gathered to help characterize a research problem and the corresponding solutions (e.g., range of intervention alternatives and evaluation settings). This information can provide a conceptual framework for developing appropriate intervention measures by refining study designs and providing support to intervention outcomes[57]. Occupational intervention research can be considered within the context of a wide research field that includes occupational safety and health, epidemiology, and industrial hygiene; such research involves broad communities including labor forces, industries, academia, and government agencies[15]. An extensive collaboration between researchers and practitioners is thus conducive to solving

Table 2. Major steps conducted in heat stress intervention research

Objective	Approach	Outcome
Task 1	Comprehensive literature review	Theoretical basis
Task 2	Publicity and exchange	Internal/external collaboration
Task 3	Study design	Study protocols
– Efficacy	– RCT in laboratory experiment	– Protocol of intermittent treadmill running test
– Effectiveness	– RCT in field experiment	– Protocol of field experiment
– Diffusion	– Field survey	– Sample of questionnaire
Task 4	Execution	Demonstration
– Efficacy	– Execution of experiment and analysis	– Efficacy of the intervention
– Effectiveness	– Execution of experiment and analysis	– Effectiveness of intervention
– Diffusion	– Administration of survey and analysis	– Acceptability of intervention
Task 5	Public forum	Practicality of intervention

practical problems on the feasibility of an intervention in representative settings[12, 15]. Prior to performing any methodological procedure, this proactive process may provide a platform through which practitioners can be engaged as intervention participants and become involved in deliberations about research findings in the subsequent research tasks.

The methodologies in intervention research have been well documented and elaborated by earlier studies[11, 57, 62, 64]. A well-structured study design for occupational intervention research mainly considers intervention characteristics, research settings (e.g., randomized controlled trials), sampling plans, and measurement instruments[11, 12]. The four major steps in the execution process are preparation, briefing, measurement, and debriefing[66–68]. Assessment preparations include the consideration of the intervention object, recruited participants, trained investigators, calibrated and synchronized equipment, availability of study sites, and recruited medical staff (if necessary). Descriptive statistics and statistically analytical techniques can be used to detect the differences between two or more groups under a specific study design.

Disseminating findings represents the end of intervention research loop in the current phase[15, 19]. Statistical and practical significance, as well as unexpected study outcomes, should be disseminated[11]. Findings should be communicated to intervention participants and relevant non-participants (e.g., stakeholders, safety and health professionals, producers of intervention products, and government agencies) who can take the necessary actions in an expeditious manner and in a form that is readily understood[15].

Conclusions

Major areas and gaps of previous heat stress intervention research in construction have been identified through a literature review. Administrative, environmental and personal engineering controls have been documented in the 35 peer-reviewed journal papers. Methodological limitations, such as sampling methods and instruments, could be the major obstacle in undertaking heat stress intervention research. There is a pressing need to develop a well-structured research framework for formulating solid and proper interventions that aid construction workers in combating heat stress. The present study follows the well-established process of occupational intervention research and establishes a 5-D model that facilitates the refinement and improvement of existing research methods from a multi-disciplinary perspective in the fields of occupational safety and health, textile science, and human biology. The proposed research framework provides a full description and definite guidelines for conducting intervention development studies. This research framework can facilitate the creation and discovery of scientific knowledge and lead to the improvement and development of practical problem solving. It provides fresh insights which are useful for expanding research areas, exploring new trends, and solving practical problems in heat stress prevention strategies. The assistance of stakeholders in soliciting sufficient participants for each phase is pivotal to the success of the research. Despite its challenges, it is recognized that intervention research can provide a platform for facilitating communication and collaboration among academicians and practitioners and therefore can stimulate and nurture the growth of the promising heat stress intervention research area.

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