Received: 19 July 2022 | Revised: 13 December 2022 | Accepted: 10 January 2023

DOI: 10.1002/ajim.23462

REVIEW ARTICLE

AMERICAN JOURNAL OF INDUSTRIAL MEDICINE WILEY

Limitations associated with thermoregulation and cardiovascular research assessing laborers performing work in the heat

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Abstract

Purpose: To quantify the current literature and limitations associated with research examining thermoregulatory and cardiovascular strain in laborers working in the heat.

Methods: PubMed, SCOPUS, and SPORTDiscus were searched for terms related to the cardiovascular system, heat stress, and physical work. Qualifying studies included adult participants (18–65 years old), a labor-intensive environment or exercise protocol simulating a labor environment, a minimum duration of 120 min of physical work, and environmental heat stress (ambient temperature ≥26.0°C and ≥30% relative humidity). Studies included at least one of the following outcomes: pre- and peak physical work, core temperature, heart rate (HR), systolic blood pressure, diastolic blood pressure, HR variability, and rate pressure product.

Results: Twenty-one out of 1559 potential studies qualified from our search. There was a total of 598 participants (mean = 28 ± 50 participants per study, range = 4–238 participants per study), which included 51 females (8.5%) and 547 males (91.5%). Of the participants, 3.8% had cardiovascular risk factors (diabetes: n = 10; hypertension: n = 13) and 96.2% were characterized as "healthy". Fifty-seven percent of the included studies were performed in a laboratory setting.

Conclusions: Studies were predominantly in men (91.5%), laboratory settings (57%), and "healthy" individuals (96.2%). To advance equity in protection against occupational heat stress and better inform future heat safety recommendations to protect all workers, future studies must focus on addressing these limitations. Employers, supervisors, and other safety stakeholders should consider these limitations while implementing current heat safety recommendations.

KEYWORDS
cardiovascular, occupational heat stress, systematic review, thermoregulation, workers

1 | INTRODUCTION

Environmental heat exposure endangers millions of people worldwide and has become a significant public health crisis.[1–9] The frequency of heat-related injuries and fatalities continues to rise as climate change increases the duration and intensity of heat waves.[1–3] Laborers are expected to perform intense work for prolonged periods of time in the heat, placing them at greater risk of heat-related injuries and illnesses.[4–10] A meta-analysis by Binazzi et al.[11] that included multi-country observational studies examining heat stress and occupational injury occurrence reported a statistically significant increase in relative risk of occupational injuries with increasing heat exposure. In outdoor construction workers, research has reported a 0.5% increase in the odds of traumatic injuries per 1°C increase in maximum daily humidex (odds ratio: 1.005 [95% confidence interval, CI: 1.003–1.007]).[12] In conjunction with increased injuries and injury claims,[13] Morrissey et al.[14] (in review) reported that within Occupational Safety and Health Administration (OSHA)-reported, exertion-related injuries and fatalities between 2015 and 2022, heat-related cases accounted for 91.9% and 87.6%, respectively. This is not surprising as the thermoregulatory and cardiovascular systems are substantially challenged under heat stress as blood flow redistribution and sweating must occur to facilitate heat dissipation for the maintenance of heat balance.[15,16] During physical work in the heat, the heart must satisfy elevated skin and skeletal muscle demand for blood flow, which further exacerbates the cardiovascular and heat-illness risk.[17,18] Performing physical work in extreme heat may increase the risk of ischemic heart disease, stroke, heart failure, and myocardial infarction.[6,18–20]

Given the tremendous threat to worker health and safety,[4,12,21–23] in September 2021, the Biden–Harris Administration launched an interagency effort to respond to the extreme heat that negatively affects working populations, children, and seniors.[24] This federal action included the immediate mobilization of the rulemaking process to develop a mandated heat stress standard, which consisted of an advanced notice of proposed rulemaking for Heat Injury and Illness Prevention in Outdoor and Indoor Work Settings (Docket OSHA-2021-0009).[24,25] As the process of heat stress policy reform continues to unfold, OSHA is looking to the existing literature to structure evidence-based regulations across all industries. As recent developments in health policy are rooted in high-quality, original research, it is critical to observe what current literature exists to determine: (1) what occupational heat stress studies are being utilized to inform occupational heat stress policy, (2) what limitations does this literature have, and (3) what populations of workers are not represented within this research. These limitations will allow key heat safety stakeholders to create a comprehensive research agenda in hopes of providing strictly evidence-based guidelines within the mandated standard. As heat illnesses during work in the heat are the result of exertion-related activity, we have narrowed our focus to thermoregulatory and cardiovascular literature.

Therefore, the purpose of this systematic review was twofold: (1) to perform a critical assessment of the current literature examining thermoregulatory and cardiovascular strain during physical work in the heat and (2) to assist future investigations by identifying gaps in knowledge associated with potential thermoregulatory and cardiovascular strain measured in laborers while working in the heat. These aims highlight what existing literature a being utilized to inform OSHA's heat stress standard and what important industrial settings and populations of workers are not represented appropriately.

2 | MATERIALS AND METHODS

We performed a Boolean search with search terms related to the cardiovascular system, heat stress, and physical work to identify included studies (October 2022, Supporting Information: Appendix A). The searches were performed with the assistance of a medical librarian and only recent articles were considered (date limit set at Year 2000). The following databases were systematically searched: PubMed, SCOPUS, and SportDiscus. Website searches and citation searching were utilized as additional methods. This systematic review was consistent with the *P*referred *R*eporting *I*tems for *S*ystematic *R*eviews and *M*eta-*A*nalyses (PRISMA) 2020 statement[26] and registered on PROSPERO (registration number: CRD4202149966).

Studies were considered eligible if they met the following inclusion criteria: (1) adults between 18 and 65 years old; (2) performed in a labor environment[4] or an exercise protocol, which simulated a labor environment; (3) minimum duration of 120 min, (4) included heat exposure defined by specific environmental conditions (ambient temperature ≥26.0°C and ≥30% relative humidity); (5) included a physical work bout; (6) included a valid assessment of core temperature (Tcore) (esophageal, rectal, gastrointestinal temperature)[27]; (7) included at least one of the following cardiovascular outcomes: pre- and peak physical work heart rate (HR), systolic blood pressure (SBP), diastolic blood pressure (DBP) HR variability (HRV), and rate pressure product (RPP). All studies were peer-reviewed, and those published in a non-English language were translated using Google Translate. Systematic reviews, editorials, magazine articles, and conference proceedings were excluded. After obtaining all articles collected across all databases and other methods (and removing duplicates), articles were screened by title and abstract and then by full text. Three independent coders triaged the records (M. C. M., S. P. L., and G. J. B.).

Data were extracted using a standardized coding form.[28] We coded characteristics related to participant anthropometrics, participant demographics, occupation or working population of interest, type of physical work performed, physical work duration and intensity, location, environmental conditions, and Tcore response, as well as physical work and cardiovascular outcomes (HR, SBP, DBP, HRV, and RPP), for all studies. When studies had multiple experimental arms or interventions, they were treated as independent interventions.

We evaluated the risk of bias (ROB) and methodological quality of the included studies to assess the weight of evidence for each finding and address biases.[29–33] ROB refers to the risk of a systematic error or deviation from the truth within included studies.[31,34] All methodological flaws do not automatically suggest that the data are biased; some methodological flaws include problems with reporting and quality (i.e., bias can occur in well-conducted studies). As both randomized and nonrandomized study designs were included in this systematic review, we utilized the Cochrane RoB2 Tool to assess ROB of randomized controlled trials.[32] The five evidenced-based ROB domains were related to randomization, deviations from intended interventions, missing outcome data, measurement of outcomes, and selection of reported results. ROB for nonrandomized studies was examined using the ROBINS-I (Risk Of Bias In Nonrandomized Studies-of Interventions).[31] The ROBINS-I assesses ROB within five domains: confounders, selection of participants in the study, classification of interventions, deviations of intended interventions, missing data, measurement of outcomes, and selection of the reported results. For both ROB Assessment Tools, each study was scored as either: unclear ROB, high level for ROB, and low level for ROB.

To assess the methodological quality, each study was evaluated using the modified Downs and Black checklist.[33] Questions within the Downs and Black checklist were modified to reflect the objectives evaluated within the systematic review. The Downs and Black checklist categories of possible bias include: (1) reporting; (2) external validity; (3) bias (internal validity); (4) confounding; and (5) power. Methodological study quality was reported as the percentage of items satisfied out of a possible 30 items. The overall methodological quality was classified as: low (≤15 points, <50%), moderate (>15–24 points, 50%–79%), and high (≥25 points, ≥80%).[33] A detailed description of each of the modified Downs and Black checklist items is provided elsewhere.[33]

Two coders (M. C. M. and G. J. B.) independently extracted and entered study information for ROB and methodological quality assessments. All disagreements were resolved through discussion.

2.1 | Statistical analyses

Descriptive statistics are reported as weighted mean ± standard deviation (SD).

3 | RESULTS

3.1 | Description of studies

Out of 1559 potential studies in our search, 21 studies qualified, which yielded 71 interventions (Figure 1).[10,35–54] No studies were translated using Google Translate. The descriptive characteristics of each intervention are presented in Table 1. There was a total of 598 participants (mean = 28 ± 50 participants per study, range = 4–238 participants per study), which included 51 females (8.5%) and 547 males (91.5%) (Figure 2). Participants in the included studies were 41 ± 15 years old, 175.9 ± 4.6 cm (height), and approximately 81.41 ± 9.02 kg (body mass). Of the participants, 3.8% had

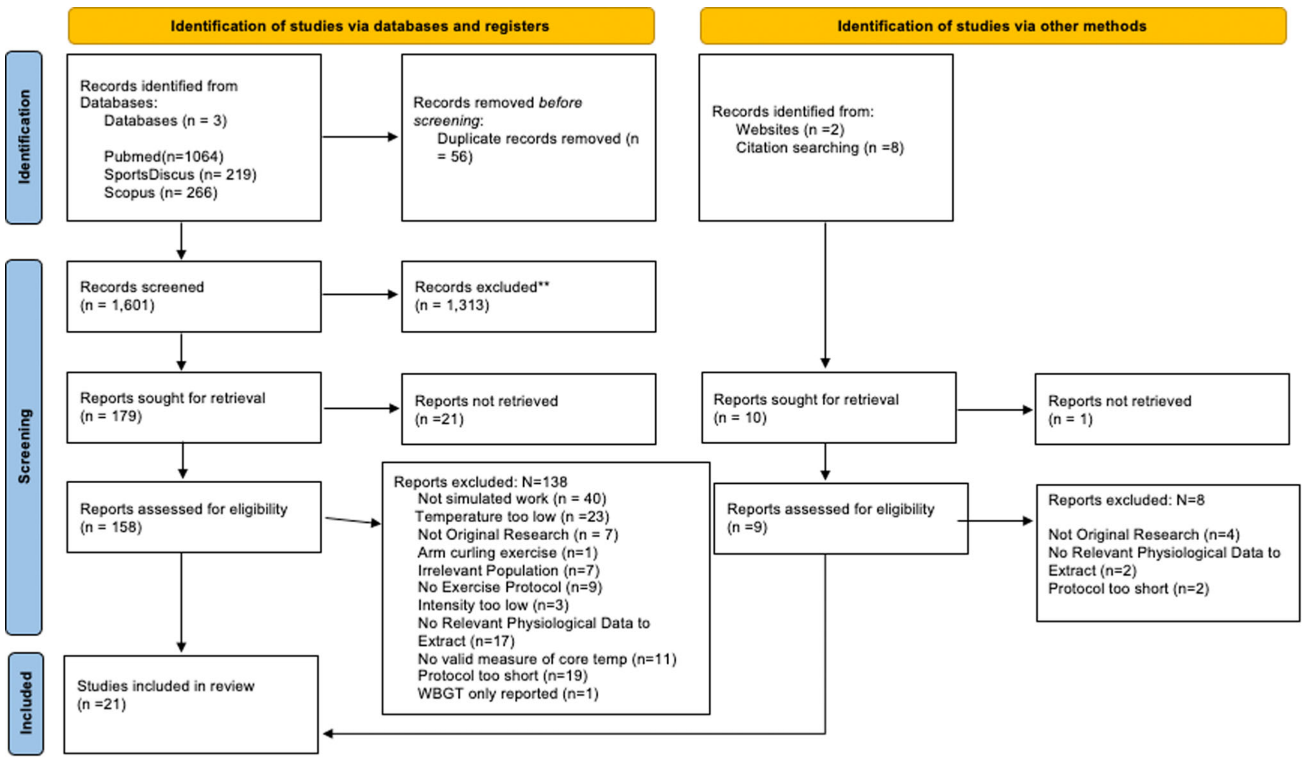

FIGURE 1 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow Chart. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Descriptive characteristics of included studies.

Studies	N	Subject characteristics	Study design	Trials (#)	Lab study?	Description of intervention	Intervention time (min)	Environment	Description of personal protective gear	Outcomes
Brearley et al.[36]	10	Male (n = 4) and female (n = 6) doctors, nurses, and paramedics (medical team)	Single trial	1	No	Simulated rescue (shopping center collapse and fire)	150	29.3°C, 50.3% RH, apparent: 27.9°C	Not specified	HR, Tcore
Brearley et al.[35]	20	Male electrical utility workers	Single trial	1	No	Maintenance of electrical structures, regular work shift	480–720	33.7°C, 54% RH WBGT: 32°C	Compression undergarments, coverall suit, gloves, hard hat	HR, Tcore
Ciuha et al.[37]	10	Healthy, physically active, unacclimatized males	Cross-over	4	Yes	Three cooling interventions versus control Two bouts of 50 min treadmill walking at 3.2 m/h with 20 min rest in between	120	45.6°C,22% RH in climate-controlled chamber	Military gear with modifications and without modifications	HR, Tcore
Horn et al.[53]	9	Male (n = 6) and female (n = 3) firefighters	Single trial	1	No	3 h of intermittent live fire training, the training included coordinating fireground operation, advanced hose and extinguish fire, forcible entry, search, and rescue	180	Building with live fire	Firefighter turnout suit, full gear	HR, Tcore
Hunt et al.[54]	15	Male (n = 14) and female (n = 1) mine crew blast workers	Single trial	1	No	Regular work shift	720	32.6°C, 34.8% RH WBGT: 28.9°C	Firefighter Turnout suit, full gear	HR, Tcore
Ioannou et al.[10]	238	Construction, tourism, agriculture workers in Spain, Cyprus, Greece, Qatar (209 men, 29 women)	Cohort	18	No	Regular work shift	Full work shift (480–600)	~26.6–36.3°C, 49.8%–54.3% RH WBGT: 19.2–29.2°C	Work protective gear	HR, Tcore
Kaltsatou et al.[38]	9	Older working males	Cross-over	3	Yes	Three different work-to-rest ratio protocol: (1) Cycling at moderate to heavy intensity according to ACGIH (2) Six 15-min bout cycling with 5 min recovery at moderate to heavy intensity according to ACGIH (3) Four 15-min bout cycling with 15 min recovery at moderate to heavy intensity according to ACGIH	120	36°C, 38% RH WBGT: 28°C, in direct calorimeter; 40°C, 30% RH WBGT: 29°C, in direct calorimeter	Not specified	HR, HRV, Tcore

TABLE 1 (Continued)

Studies	N	Subject characteristics	Study design	Trials (#)	Lab study?	Description of intervention	Intervention time (min)	Environment	Description of personal protective gear	Outcomes
Lamarche et al.[39]	4	Male electrical utilities workers	Consecutive trials	2	No	Day 1 and Day 2: Work shift that consisted of 240 min of work and 60 min of recovery Replaced old utility poles, install new poles, dig holes, remove insulation from power lines	300	34.7°C, 51% RH WBGT: 29.4°C; 32.7°C, 68% RH WBGT: 29.7°C, in direct calorimeter	Standard work uniform	HR, Tcore
Larsen et al.[40]	10	Male volunteer wildland firefighters	Cross-over	2	Yes	Hot versus thermoneutral condition Protocol: Simulated wildland fighter activity consisting of raking for 12 min, followed by six 8-min low-intensity stepping and 20-min rest bouts	180	Hot: 45°C, 26.9% RH Thermoneutral: 18°C, 26.9% RH in climate-controlled chamber	Wildland firefighter turnout suit, full gear	HR, Tcore
Lutz et al.[41]	31	Male miners	Single trial	1	No	Ladder climbing, cutting, electrical, jumbo drill operation, maintenance, mucking, unloading/loading, welding, troubleshooting/supervising	480	32.8°C, 70% RH	Long-sleeved cotton jumpsuit, rubber or leather boots, hard hat with lamp, safety goggles, gloves	HR, Tcore
MacCartney et al.[42]	9	Older male workers	Consecutive trials	2	Yes	Day 1 and Day 2: three 30 min cycling bouts at 150, 200, and 250 W/m^2 with 15 min recovery between bouts	135	40°C, 20% RH	Not specified	HR, HRV, Tcore
Meade et al.[44]	32	Male ground electrical utilities workers	Single trial	1	No	Simulated regular electrical utilities work shift (three groups of different electrical utilities workers)	~174–207	32–35°C, 48%–59% RH	Standard work uniform (work pants, long sleeve button up, hard hat, gloves, steel-toe boots)	HR, Tcore
Meade et al.[43]	9	Healthy young males	Cross-over	3	Yes	Three different work-to-rest ratios Continuous cycling at 360 W; 100 min of active work, 84 min of recovery; 75% of work shift at light intensity, 60% of work at moderate intensity, and 4% at heavy intensity	120–184	Continuous: 41°C, 19.5% RH WBGT: 28.0°C WR 3:1: 43°C, 17.5% RH WBGT: 29.0°C WR 1:1: 46.5°C, 17.5% RH WBGT: 31.5°C	100% cotton work uniform (coveralls, work pants, hard hat)	HR, Tcore

(Continues)

TABLE 1 (Continued)

Studies	N	Subject characteristics	Study design	Trials (#)	Lab study?	Description of intervention	Intervention time (min)	Environment	Description of personal protective gear	Outcomes
Notley et al.[45]	9	Physically active older males	Consecutive trials	2	Yes	Day 1 and Day 2: 30-min bout of cycling at 150 W, followed by 15 min rest, 30-min bout of cycling at 200 W, followed by 15 min rest, 30-min bout of cycling at 250 W, followed by 15 min rest Three 2-h bouts of 30 min of treadmill walking at 360 W, followed by 10 min rest, recovery period of 2 h at the end of work simulation	150–390	40°C, 20% RH in direct calorimeter; 38°C, 34% RH in direct calorimeter	Cotton work uniform (coveralls, short-sleeved shirt, socks)	HR, Tcore
Notley et al.[46]	50	Young males (n = 13), older males (n = 14), older males with Type 2 diabetes (n = 10), older males with hypertension (n = 13)	Cross-over	4 (only 3 met the inclusion criteria)	Yes	Three environmental conditions meeting inclusion criteria (WBGT: 24°C, 28°C, and 32°C) Continuous treadmill walking at 200 W/m^2 for 180 min with 60 min recovery	240	WBGT 24°C Trial: 31.7°C, 35% RH WBGT: 28°C Trial: 36.6°C, 35 RH WBGT: 32°C Trial: 41.4°C, 35% RH	Cotton work uniform (coveralls, short-sleeved shirt, socks)	HR, Tcore
Notley et al.[47]	34	Young males (n = 19) and Young females (n = 15)	Cross-over	4 (only 3 met the inclusion criteria)	Yes	Three environmental conditions meeting the inclusion criteria (WBGT: 24°C, 28°C, and 32°C) Continuous treadmill walking at 200 W/m^2 for 180 min with 60 min recovery	240	WBGT 24°C Trial: 31.7°C, 35% RH WBGT: 28°C Trial: 36.6°C, 35 RH WBGT: 32°C Trial: 41.4°C, 35% RH	Cotton work uniform (coveralls, short-sleeved shirt, socks)	HR, Tcore
Uchiyama et al.[49]	13	Physically active males	Cross-over	2	Yes	Two different work-to-rest ratios Current practice trial: 180 min walking at 11 on Borg Rating of Perceived Exertion Scale with one 30 min break and one 15 min break Experimental trial: 180 min walking at 11 on Borg Rating of Perceived Exertion Scale with one 15 min break and three 10 min breaks	225	37°C, 35% RH		HR, Tcore

TABLE 1 (Continued)

Studies	*N*	Subject characteristics	Study design	Trials (#)	Lab study?	Description of intervention	Intervention time (min)	Environment	Description of personal protective gear	Outcomes
Stapleton et al.[48]	8	Physically active males	Cross-over	6	Yes	Three different ensembles in two different environments (hot-dry, hot-wet) Protocol: Six 15-min bouts of cycling with 5 min recovery at 360 W (5 interventions)	120	Hot-dry: 46°C, 10% RH Hot-west: 33°C, 60% RH WBGT: 29°C	Not specified; modified work uniform; standard work uniform	HR, Tcore
Wright et al.[50]	28	Nonheat acclimatized young and older males	Cross-over	2	Yes	Two environmental conditions (hot-dry, hot-humid) Four 15-min bouts of cycling at 400 W separated by 15 min rest with a 60-min resting recovery	120	Hot-dry: 35°C, 20% RH Hot-humid: 35°C, 60% RH In climate-controlled chamber	Shorts and sandals	HR, PV, Tcore
Wright-Beatty et al.[51]	36	Male older and young firefighters and nonfirefighters	Cross-over	2	Yes	Two environmental conditions (hot-dry, hot-humid) Four 15-min bouts of cycling at 400 W separated by 15 min rest with a 60-min resting recovery	120	Hot-dry: 35°C, 20% RH Hot-humid: 35°C, 60% RH In climate-controlled chamber	Shorts and sandals	HR, Tcore
Zhao et al.[52]	14	Male construction workers	Cross-over	2	No	Cooling versus control Steel bar fixing work	420	37°C, 60% RH	T-shirt, pair of trousers, vest	HR, Tcore

Note: A, B includes different studies from the same author and year.

Abbreviations: ACGIH, American Conference of Governmental Industrial Hygienists; HR, heart rate; RH, relative; TCore, core temperature.

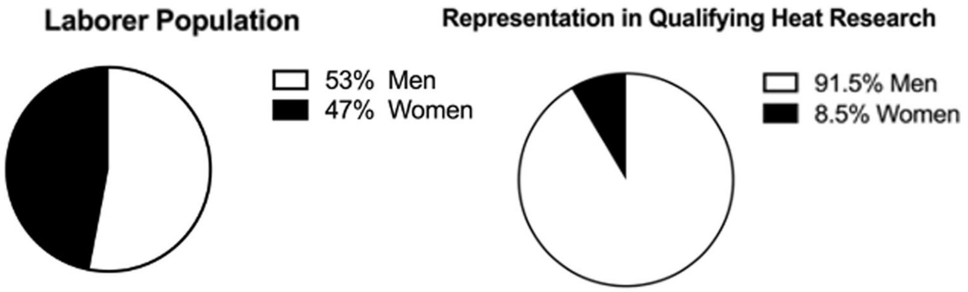

FIGURE 2 Percentage of men and women in the United States Laboring Workforce compared to the percentage represented in included studies.

TABLE 2 ROB for randomized controlled trials evaluated using the revised Cochrane RROB Tool (RoB2).

			ROB judgment for bias rising from the/due to					
First author, last name	Language	Year	Randomization process	Deviation from intended interventions	Missing outcome data	Measurement of outcomes	Selection of reported results	Overall rating
Ciuha	English	2016	SC	SC	SC	HR	SC	HR
Larsen	English	2015	LR	SC	LR	SC	SC	SC
Kaltsatou	English	2020	LR	LR	LR	LR	LR	SC
Stapleton	English	2012	SC	LR	LR	SC	SC	SC
Uchiyama	English	2022	SC	LR	LR	SC	LR	SC

Abbreviations: HR, high risk; LR, low risk; ROB, Risk of Bias; SC, some concerns.

cardiovascular risk factors (diabetes: $n = 10$; hypertension: $n = 13$) and 96.2% were characterized as "healthy." Seven studies performed a maximal oxygen consumption (VO_2max) test with an average VO_2max of 43.01 ± 8.76 mL/kg/min. According to the American College of Sports Medicine guidelines, the average VO_2max when applied to the average age was good for men of this age and superior for women.[55] The average participant body fat was 20.3 ± 3.99% ($k = 9$).

Of the studies included, 12 were performed in a laboratory setting (57%) and 9 were performed in a field setting (43%), with 5 (23.8%) including randomized controlled trials and 16 including nonrandomized controlled trials (76.2%). Participants in 10 studies wore personal protective equipment (PPE) (47.6%). The environmental conditions of the interventions (71 interventions) had an average ambient temperature of 36.4 ± 4.6°C ($k = 20$, range: 26.6–46°C) and average relative humidity of 37.63 ± 15.06% (range: 10%–69.9%). The average intervention duration was 237.04 ± 128.54 min. The following populations were included: (1) structural firefighters ($k = 2$, interventions: 5), (2) wildland firefighters ($k = 1$, interventions: 1), (3) construction workers ($k = 2$, interventions: 4), (3) electrical utility workers ($k = 3$, interventions: 7), (4) miners ($k = 2$, interventions: 2); (5) agriculture workers ($k = 1$, interventions: 2), (6) physically active populations performing simulated work ($k = 7$, interventions: 44), (7) tourism workers ($k = 1$, interventions: 2), (8) doctors, nurses, and emergency service workers ($k = 1$, interventions: 1), (9) "older workers" ($k = 1$, interventions: 3). Of note, in the current study, there were multiple studies with many occupations included.

3.2 | Methodological quality and ROB

Cochrane RoB2 ($k = 5$) for randomized controlled trials reported that one study exhibited high risk and three studies exhibited some concerns (Table 2). The ROBINS-I assessment for nonrandomized controlled trials revealed that two studies were low risk and 15 were moderate risk (Table 3).

For methodological quality, the Downs and Black Checklist Assessment Tool found that 3 studies exhibited low methodological quality and 18 studies exhibited moderate methodological quality (Table 4). Methodological quality ranged from 46% to 70% of the items satisfied.

4 | DISCUSSION

This study aimed to provide an in-depth assessment of the current literature evaluating thermoregulatory and cardiovascular strain associated with physical work in the heat. This assessment was then utilized to identify limitations within the current literature and determine what populations of workers are not represented in this

TABLE 3 ROB for nonrandomized controlled trials evaluated using the ROBINS-I.

			ROB judgment for bias rising from the/due to							
First author, last name	Language	Year	Confounders	Selection of participants in the study	Classification of interventions	Deviations from intended interventions	Missing data	Measurements of outcomes	Selection of the reported result	Overall rating
Brearley	English	2013	MR	MR	LR	LR	LR	LR	NI	MR
Brearley	English	2015	MR	MR	MR	LR	LR	LR	LR	MR
Horn	English	2013	LR	LR	LR	MR	MR	MR	LR	MR
Hunt	English	2014	MR	LR	LR	LR	LR	LR	LR	MR
Ioannou	English	2021	MR	MR	LR	LR	LR	LR	LR	MR
Lamarche	English	2017	MR	LR	LR	LR	LR	MR	LR	MR
Lutz	English	2014	LR	MR	LR	LR	LR	LR	NI	MR
MacCartney	English	2020	MR	MR	MR	LR	LR	LR	NI	MR
Meade	English	2015	MR	MR	LR	LR	LR	MR	NI	MR
Meade	English	2016	LR	LR	LR	LR	LR	LR	NI	LR
Notley	English	2018	MR	MR	MR	LR	LR	MR	NI	MR
Notley	English	2021	MR	MR	LR	LR	LR	LR	NI	MR
Notley	English	2022	MR	MR	LR	LR	LR	LR	NI	MR
Wright	English	2015	MR	LR	MR	LR	LR	LR	LR	MR
Wright-Beatty	English	2014	MR	LR	MR	LR	LR	LR	LR	MR
Zhao	English	2017	LR	LR	LR	LR	LR	NI	MR	LR

Abbreviations: CR, critical risk; LR, low risk; MR, moderate risk; NI, no information; ROB, Risk of Bias; SR, serious risk.

research. Identifying limitations is critical to developing an appropriate research agenda and advancing our understanding to create stronger evidence-based heat stress management plans in the occupational setting. From this investigation, a total of 21 studies were identified, yielding 71 total interventions. Studies were predominantly in men (91.5%), "healthy" (96.2%) participants, and in laboratory settings (57%). Participants were middle-aged (average: 41 ± 15) and participated in interventions approximately 237 min long. These results indicate there are several limitations that must be considered to fully understand the physiological strain imposed on all laborers working in the heat. Moreover, a "one-size-fits-all" approach to heat stress management should be adopted with caution as current research does not reflect all working populations who work in the heat (i.e., demographics, types of work).

Unsurprisingly, the existing literature exhibits a large sex disparity with only 8.5% of participants being females (n = 51). This is particularly troublesome as the US Department of Labor reported that 47% of the US labor force are females, accounting for approximately 75 million people[56] (Figure 2). Unfortunately, this trend of under-representation has been observed across all investigations related to thermal physiology, with females accounting for only 30% of studies conducted to date.[57]

As physiological differences do exist between men and women,[47,58–63] current occupational heat stress prevention strategies and recommendations stem from original research performed in men.[64] For example, the NIOSH Recommended Alert Limits and Recommended Exposure Limits originated from Lind,[64] where three male mine rescue personnel were tested to develop heat tolerance thresholds for safety criteria.[65] Notley et al.,[47] included in the current review, is the first investigation to examine the validity of American Conference of Governmental Industrial Hygienists (ACGIH) guidelines in women and reported no significant sex differences in thermal or cardiovascular strain when performing at a fixed metabolic rate (200 W/m^2) for 180 min in various environmental conditions. As indicated by the authors, the findings are restricted to 180 min and equal metabolic rate based on each participant's body surface area to body mass ratio. Moreover, under regular working conditions, both men and women are responsible for performing the same absolute work, which requires divergent amounts of metabolic heat to perform the same task. The other qualifying studies that included women[10,36,53,54] were conducted during a regular shift or simulated work event; however, the data were not separated to examine differences in physiological responses between sexes.

Our findings reported that only 3.8% of the qualifying literature included participants with chronic health conditions such as diabetes and hypertension. This distribution does not align with US working population as approximately 45% of all Americans suffer from at least one chronic disease.[66] As this number continues to grow, the number of Americans who work beyond the traditional retirement age

TABLE 4 Methodological quality assessment using the Downs and Black Assessment Tool.

First author, last name	Publishing language	Publishing year	Methodology quality criteria Reporting (13)[a]	External Validity (3)	Bias (7)	Confounding (6)	Power (1)	Total (30)
Brearley	English	2013	7	2	5	1	0	15
Brearley	English	2015	10	3	5	2	0	20
Ciuha	English	2016	7	1	3	3	0	14
Horn	English	2013	10	3	2	4	0	19
Hunt	English	2014	7	2	5	3	0	17
Ioannou	English	2021	8	3	3	3	0	17
Kaltsatou	English	2013	7	0	4	4	1	16
Lamarche	English	2017	8	3	4	2	0	17
Larsen	English	2015	10	1	3	2	0	16
Lutz	English	2014	9	3	5	3	0	19
MacCartney	English	2020	8	1	4	1	0	14
Meade	English	2015	6	3	3	2	0	14
Meade	English	2016	10	0	5	4	0	19
Notley	English	2018	7	3	4	3	0	17
Notley	English	2021	8	2	5	3	0	18
Notley	English	2022	7	2	5	3	0	17
Stapleton	English	2019	9	0	5	4	0	18
Uchiyama	English	2022	10	2	5	2	1	20
Wright	English	2014	10	1	5	2	0	18
Wright-Beatty	English	2014	10	2	5	2	0	19
Zhao	English	2017	7	3	5	1	1	17

[a]Maximum number that can be scored in that criterion.

increases, and the proportion of workers who are at risk of injury due to their age and health status will increase.[39,67] This is also relevant as most deaths during heatwaves are caused by cardiovascular events and underlying cardiovascular comorbidities.[68–70] Although deaths during heatwaves occur in primarily elderly populations, research on the impact of hyperthermia and cardiovascular strain on the aging workforce with chronic health conditions remains limited.[45,68] Notley et al.,[46] within the qualifying literature, demonstrate that older men with diabetes and hypertension have a lower tolerance of uncompensable heat stress compared to older and young men without chronic disease. However, diabetes nor hypertension significantly impacted Tcore and HR responses and did not affect the validity of the current ACGIH guidelines for work limits during moderate-intensity work. It is still unclear what the effects multiple cardiovascular risk factors (i.e., physical inactivity, obesity, diabetes, dyslipidemia, hypertension, family history of cardiovascular events) may have on workers' thermoregulatory and cardiovascular responses to an acute bout of physical work in the heat.

Lastly, agricultural and construction workers are considered the most susceptible to heat-related fatalities with a fatality rate significantly higher than workers in other industries.[1,56,71,72] Interestingly, 2 of the 35 included studies examined these populations (agriculture: $k = 1$; construction: $k = 2$).[10,52] Many studies examining heat stress in workers in the agriculture and construction industry did not meet inclusion criteria for this review as invalid Tcore assessments (e.g., aural, oral, tympanic) were utilized to quantify Tcore. It has been well established that these indirect Tcore assessments are inaccurate and should not be used to quantify Tcore responses.[27,73–75] For example, Morrissey et al.[74] reported that in exertional heat stroke patients, aural temperature was 4°F (2.4°C) degrees lower than rectal thermometry, which is considered the gold standard assessment in field settings. In a field setting, gastrointestinal pills for Tcore assessment have been shown to be reliable, accurate, and valid.[27,76] Future research must implement reliable techniques while investigating thermoregulatory function during physical work in the heat in these industries that are at greater risk.

Although there are numerous strengths of this review, there are limitations that must be addressed. First, we utilized environmental conditions (ambient temperature and relative humidity) as inclusion criteria. It is well understood that occupational heat stress is a

TABLE 5 Considerations while designing studies in thermoregulatory and cardiovascular research during physical work in laborers.

Considerations	Examples
Include human participants who are reflective of the true demographics of working populations	Workers who are: female, diabetic, hypertensive, obese, older, premenopausal, postmenopausal
Exercise intervention must reflect the type of work performed in a labor setting	Walking, heavy lifting, and so on
Exercise intervention must reflect the duration of work performed in a labor setting	>4 h of work
Protocol should consider consecutive days of work that often occur in labor settings	2–6 days of work
Assess core temperature using valid measures	Gastrointestinal pill

combination of environmental conditions, encapsulating PPE, and heavy physical exertion. This review used environmental conditions to distinguish hot environments as it has been used as a common indicator of heat stress in previously published systematic reviews.[77,78] However, it should be recognized that these inclusion criteria may have excluded studies that have experienced heat stress through physical activity or PPE only. Second, the limiting factors highlighted in this review only reflect a few major considerations for future research studies. There are several considerations such as types of work performed, the intensity of work, consecutive days of work, and more that must be considered while developing research to create more informative heat stress management guidelines.

The limitations highlighted in the current review should be taken into consideration when implementing the current heat stress management recommendations proposed. As occupational health and safety organizations emphasize and utilize evidence-based information in recommendations and federal standards, research to date that examined thermoregulatory and cardiovascular strain during physical work in heat is limited to males, "healthy" individuals, and are more often performed in laboratory settings. Although these data have been extremely informative as we move forward with a federal heat stress standard, it is difficult to determine whether the recommendations can be applied to other workers such as women and workers with comorbidities such as obesity, diabetes, and hypertension. As advances in this research will take many years to address these critical gaps, at this time, employers, supervisors, and safety professionals must recognize that the guidelines may not protect all workers. Researchers should consider the factors listed in Table 5 when designing studies to address critical gaps. Addressing these considerations will create stronger evidence-based and effective heat stress mitigation strategies that protect all types of workers and advance equity in protection against occupational heat stress.

5 | CONCLUSION

The 21 qualifying studies examining cardiovascular and thermoregulatory strain during physical work in the heat suggest that the existing literature is in predominantly men (91.5%), laboratory settings (57%), and "healthy" participants (96.2%). Researchers should consider these limitations when designing future studies in this field to ensure all future heat safety recommendations can be applied to the diverse population of workers who may respond differently to heat stress. This consideration is important to advance equity in protection against occupational heat stress in all working populations who labor in the heat.

AUTHOR CONTRIBUTIONS

Margaret C. Morrissey and Douglas J. Casa contributed to the conception of the study and hypothesis generation. Margaret C. Morrissey, Sean P. Langan, and Gabrielle J. Brewer screened and coded articles. Margaret C. Morrissey and Gabrielle J. Brewer performed the quality assessment of included articles. Margaret C. Morrissey, Jeb F. Struder, Megan N. Nye, and John S. Navarro wrote the first draft of the manuscript and all authors contributed to the interpretation of the data. All authors read and approved the final manuscript.

ACKNOWLEDGMENTS

The authors would like to thank Dr. Linda Pescatello for her teachings on the best practices for conducting systematic reviews and Hilary Kraus for her assistance with the search.

CONFLICTS OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ETHICS APPROVAL AND INFORMED CONSENT

As the current study was a systematic review of existing literature, no ethics approval or informed consent was obtained.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Morrissey MC, Langan SP, Brewer GJ, et al. Limitations associated with existing thermoregulation and cardiovascular research assessing laborers performing work in the heat. *Am J Ind Med*. 2023;1-14. doi:10.1002/ajim.23462