Heat acclimation (HA) is the process of intentional and consistent exercise in the heat that results in positive physiological adaptations, which can improve exercise performance both in the heat and thermoneutral conditions. Previous research has indicated the many performance benefits of HA, however, a meta-analysis examining the magnitude of different types of performance improvement is absent. Additionally, there are several methodological discrepancies in the literature that could lead to increased variability in performance improvement following HA and no previous study has examined the impact of moderators on performance improvement following HA. Therefore, the aim of this study was two-fold; (1) to perform a meta-analysis to examine the magnitude of changes in performance following HA in maximal oxygen consumption (VO$_{2\text{max}}$), time to exhaustion, time trial, mean power, and peak power tests; (2) to determine the impact of moderators on results of these performance tests. Thirty-five studies met the inclusion/exclusion criteria with 23 studies that assessed VO$_{2\text{max}}$ ($n = 204$), 24 studies that assessed time to exhaustion ($n = 232$), 10 studies that performed time trials ($n = 101$), 7 studies that assessed mean power ($n = 67$), and 10 papers that assessed peak power ($n = 88$). Data are reported as Hedge’s $g$ effect size (ES), and 95% confidence intervals (95% CI). Statistical significance was set to $p < 0.05$, a priori. The magnitude of change following HA was analyzed, with time to exhaustion demonstrating the largest performance enhancement (ES [95% CI], 0.86 [0.71, 1.01]), followed by time trial (0.49 [0.26, 0.71]), mean power (0.37 [0.05, 0.68]), VO$_{2\text{max}}$ (0.30 [0.07, 0.53]), and peak power (0.29 [0.09, 0.48]) ($p < 0.05$). When all of the covariates were analyzed as individual models, induction method, fitness level, heat index in time to exhaustion (coefficient [95% CI]; induction method, $-0.69 [-1.01, -0.37]$, $p < 0.001$; fitness level, 0.04 [0.02, 0.06], $p < 0.001$; heat index, 0.04 [0.02, 0.07], $p < 0.0001$) and induction length in mean power (coefficient [95% CI]; induction length 0.15 [0.05, 0.25], $p = 0.002$) significantly impacted the magnitude of change. Sport scientists and researchers can use the findings from this meta-analysis to customize HA induction. For time to exhaustion improvements, HA implementation should focus on induction method and baseline fitness, while the training and recovery balance could lead to optimal time trial performance.
INTRODUCTION

Athletes in team and individual sports use a variety of training methods to achieve peak performance. One training modality that has been established is known as heat acclimation (HA) (i.e., training in a hot, artificial environment) or heat acclimatization (i.e., training in a hot, natural environment), repeatedly. HA is the process of intentional and consistent exercise in the heat that results in several positive physiological and perceptual adaptations (Armstrong and Maresh, 1991). A decrease in heart rate, internal body temperature, sweat electrolyte concentration, and perceptual measures and an increase in sweat rate and plasma volume are all positive adaptations that occur throughout HA (Périard et al., 2015; Casadio et al., 2017). While the physiological benefits of HA have been established for many years (Adolph, 1938), a growing body of literature has emerged investigating the many performance benefits of HA in hot and thermonatural environmental conditions. While the physiological and perceptual benefits of HA are the mechanisms behind enhanced exercise performance, actual result from competition, such as a faster race time, an increased time to exhaustion, or improved aerobic capacity are typically the primary outcomes.

Even still, understanding the mechanisms behind enhanced exercise performance is critical to adopting optimal training programs. Cardiovascular adaptations, including decreases in heart rate and increases in plasma volume, occur within 3–6 days of HA and are known to have a strong influence on exercise performance (Sawka et al., 2011; Périard et al., 2016). Body temperature adaptations, both internal and skin, also occur within 8 days of HA (Armstrong and Maresh, 1991) and are known to improve exercise performance (Nybo and González-Alonso, 2015). Decreases in sweat electrolyte concentration typically occurs within 5–10 days of HA and increase in sweat rate typically occurs within 5–14 days of HA (Armstrong and Maresh, 1991). These adaptations can enhance exercise performance in a hot environment, as these mechanisms improve thermoregulation (Nuccio et al., 2017). These adaptations independently and collectively improve exercise performance by helping the body thermoregulate more efficiently and reduce the overall physiological strain.

In the literature investigating HA, “performance” has been used to describe both physiological and perceptual improvements within a relative bout of exercise. “Performance” has also been used to describe the outcomes from direct measurements, such as time trial and maximal oxygen consumption ($VO_{2max}$). For this meta-analysis, performance will be defined as the result of any established test that measures exercise ability. Common tests that have been used to assess exercise performance following HA include: $VO_{2max}$, time to exhaustion, time trial, mean power, and peak power.

While the many physiological and performance benefits of HA have been reported in the literature, there are several methodological discrepancies in the literature that could lead to increased variability in these results, including fitness level, induction length, session duration, exercise intensity, induction method, induction length, environmental conditions
in performance that results from HA in VO$_{2\text{max}}$, time to exhaustion, time trial, mean power, and peak power. Second, to determine the impact of moderators on HA performance in these performance tests.

**MATERIALS AND METHODS**

A literature search was conducted using first order search terms (“acclimation,” “acclimatization,” “adaptation”) and second order search terms (“exercise,” “endurance,” “time trial,” “Wingate,” “VO$_{2\text{max}}$,” “time to exhaustion”). The search was performed in the following databases: PubMed, Scopus, CINAHL, SportDiscus, Academic Search Premier, and Cochrane Library. The search was conducted February 15, 2019.

**Selection Criteria**

The following search criteria was used to determine the suitability of each paper for this analysis. Figure 1 demonstrates the selection process for this meta-analysis. This meta-analysis only included a study if it met the following requirements:

1. The full-text was available from a peer-reviewed scientific journal in the English language.
2. The study reported a physical performance test outcome for pre and post HA intervention. Cognitive tests were not included in this analysis because the purpose was to assess the effectiveness of HA on various physical performance tests.
3. Only studies that conducted HA were included (not heat acclimatization). The term “acclimatization” was included in the search terms because “acclimation” and “acclimatization” are sometimes used interchangeably in previous research.
4. The mode of exercise during HA occurred on a cycle ergometer or a treadmill. These methods of exercise have high external validity and will be included to control for variability that may be introduced with other methods (i.e., sauna, stair- stepping).
5. The study reported findings from at least four participants to ensure appropriate power for each of the studies.
6. For studies to be included in the time to exhaustion analysis, the baseline test (prior to the start of HA) should be stopped due to volitional fatigue or the laboratory cut-points (such as internal body temperature >40°C), not because of testing time.

**Classification of the Studies**

Of the 74 peer-reviewed studies identified, 35 met the inclusion criteria. These studies were categorized by the researchers by type of performance test. Upon review, five types of tests were established: (1) VO$_{2\text{max}}$, (2) time to exhaustion, (3) time trial, (4) mean power, and (5) peak power.

**Data Extraction**

Studies that involved an additional intervention to HA were included in the analysis only if there was no difference between the control group and the intervention group. In cases that reported differences, only the control group was included.

**Study Quality Assessment**

The PEDro scale was not used for the inclusion criteria, however, a quality assessment is included in the results section (Tables 1–5). On this scale, a “high quality” study will score ≥ 7; a “moderate quality” study will score 5 or 6; a “poor quality” study will score ≤ 4 (Maher et al., 2003; Yamato et al., 2017). To assess for publication bias, funnel plots of each performance test can be seen in the supplementary material (Supplementary Figures 1–5).

**Data Analysis**

This meta-analysis was performed in Comprehensive Meta-Analysis software (version 2.2.064, Biostat company, Englewood, NJ, USA). Studies included in this analysis reported data to determine the changes within group, between pre and post HA. In the event that correlation values were not available, the lowest available correlation value for that test was utilized to calculate the effect size. Data are reported as mean (M), standard deviation (SD) mean difference (MD), Hedge’s g effect size (ES), and 95% confidence intervals (95% CI). Statistical significance was set to $p < 0.05$, a priori.

To determine the effects of moderators on outcomes in performance, a meta-regression was performed. A separate meta-regression was performed for each performance test type and moderators were entered separately as individual models in the analysis. Moderators that were considered for all test types in this analysis included: fitness level, induction method, heat index of induction, and heat index of testing. For the “fitness level” moderator, baseline (prior to HA induction) VO$_{2\text{max}}$ levels were utilized. Induction length was entered as a continuous variable as the number of days utilized for HA induction. Session duration was entered as a continuous variable as the total number of minutes for each session throughout HA induction. In cases that involved a progressive duration protocol, the average duration time was entered. Exercise intensity was defined as “low,” “moderate,” and “high,” with “low” being defined as <55% VO$_{2\text{max}}$, “moderate” between 55 and 70% VO$_{2\text{max}}$ or isothermal, and “high” being greater than 70% VO$_{2\text{max}}$ and “low” was set as the reference group. Induction method was defined as “controlled work rate” or “isothermal,” with “controlled work rate” referring to an intensity that was set by the investigator throughout HA induction and “isothermal,” referring to HA sessions adjusting the exercise intensity seeking to maintain the internal body temperature to a pre-determined criteria (typically 38.5°C). For this moderator, “controlled work rate” was set as the reference group. Environmental conditions of both induction and testing were measured as heat index and were calculated from reported environmental conditions. Tests were included if they were performed in hot (>25°C) or thermoneutral (<25°C) environmental conditions. Three of the time to exhaustion tests were performed in thermoneutral environments. Twenty of the time to exhaustion tests were performed in a hot environment. Two studies did not report the environmental conditions of the testing sessions. In terms of mean power, one study conducted the performance test in a thermoneutral environmental condition. Of the VO$_{2\text{max}}$ tests, nine were performed in thermoneutral
FIGURE 1 | Flow chart summary of the study selection process.
### Results

#### Search Results

In total, 2,527 articles were found. Of those articles, 35 met the inclusion/exclusion criteria with 23 studies that assessed VO\textsubscript{2max} (n = 204), 24 studies that assessed time to exhaustion (n = 232), 10 studies that performed time trials (n = 101), 7 studies that assessed mean power (n = 67), and 10 studies that assessed peak power (n = 88). The fitness level prior to the start of HA was reported (M ± SD; VO\textsubscript{2max}, 53.7 ± 6.8 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}; time to exhaustion 49.2 ± 8.1 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}; time trial, 52.3 ± 9.0 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}; mean power, 53.8 ± 9.2 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}; peak power, 53.1 ± 7.4 ml·kg\textsuperscript{-1}·min\textsuperscript{-1}. Most studies investigated only males, however, some of the studies reported female data. The quality of the included manuscripts was assessed by two readers using the PEDro scale (M ± SD; 5.6 ± 1.1). The nature of HA induction does not allow for blinding of the participants. Descriptive information about each of the studies for each performance test type can be seen in Tables 1–5.

#### Impact of HA on Various Performance Tests

HA had a positive impact on performance, regardless of testing type (ES [95% CI]; 0.53 [0.44, 0.63], p < 0.001). HA induced positive adaptions for each performance test [MD [95% CI]; time to exhaustion, 144.30 s [128.30, 160.31], p < 0.001; time trial, 45.60 s [22.80, 68.40], p < 0.001; mean power, 12 W [2.08, 22.37], p = 0.02; VO\textsubscript{2max}, 1.32 ml·kg\textsuperscript{-1}·min\textsuperscript{-1} [0.20, 2.43], p = 0.02; peak power 15 W [8.90, 21.09], p < 0.001]. The magnitude of change following HA induction was analyzed, with time to exhaustion demonstrating the largest performance enhancement, followed by time trial, mean power, VO\textsubscript{2max}, and peak power (ES [95% CI]; time to exhaustion, 0.86 [0.71, 1.01], p < 0.001; time trial, 0.49 [0.26, 0.71], p < 0.001; mean power, 0.37 [0.05, 0.68], p < 0.001; VO\textsubscript{2max}, 0.30 [0.07, 0.53], p = 0.012; peak power, 0.29 [0.09, 0.48], p < 0.001) (Figure 2). ES for each of the studies

### Table 1 | VO\textsubscript{2max} descriptive table.

| References | n  | Induction method* | Induction length (Days) | Session duration (min) | Exercise intensity# | Heat index induction | Heat index testing (ml·kg\textsuperscript{-1}·min\textsuperscript{-1}) | Baseline fitness | PEDro |
|------------|----|-------------------|-------------------------|------------------------|---------------------|----------------------|-----------------------------------|----------------|--------|
| Horstman and Christensen (1982) A & B | 6  | Controlled work rate | 11                      | 68                     | Low                 | 54                   | N/A                               | 51.4           | 5      |
| King et al. (1985) | 10 | Controlled work rate | 8                       | 90                     | Low                 | 43                   | 43                               | 46.1           | 4      |
| Pivarnik et al. (1987) | 16 | Controlled work rate | 6                       | 90                     | Moderate            | 43                   | 43                               | 44.2           | 4      |
| Febroia et al. (1994) | 13 | Controlled work rate | 7                       | 90                     | Low                 | 43                   | 39                               | 68.1           | 7      |
| Aoyagi et al. (1998) | 6  | Controlled work rate | 6                       | 60                     | Low                 | 43                   | 43                               | 45.1           | 7      |
| A, B, C, & D | 8  | Controlled work rate | 6                       | 150                    | Low                 | 47                   | 43                               | 49.5           | 7      |
| Lorenzo et al. (2010) | 12 | Controlled work rate | 10                      | 90                     | Low                 | 43                   | 39                               | 66.9           | 4      |
| Chen et al. (2013) A & B | 7  | Controlled work rate | 5                       | 35                     | Moderate            | 51                   | 24                               | 53.0           | 7      |
| Molloy et al. (2013) A & B | 9  | Controlled work rate | 14                      | 30                     | High                | 36                   | 22                               | 57.1           | 6      |
| Keiser et al. (2015) | 8  | Controlled work rate | 10                      | 90                     | Low                 | 39                   | 39                               | 58.1           | 7      |
| DiLeo et al. (2016) | 10 | Controlled work rate | 5                       | 90                     | Low                 | 47                   | 47                               | 50.0           | 4      |
| Neal et al. (2016a) | 10 | Isothermal          | 5                       | 90                     | Moderate            | 55                   | 22                               | 63.3           | 6      |
| Neal et al. (2016b) A & B | 8  | Isothermal          | 11                      | 90                     | Moderate            | 55                   | 20                               | 56.9           | 6      |
| James et al. (2017) | 10 | Isothermal          | 11                      | 90                     | Moderate            | 55                   | 20                               | 56.9           | 6      |
| Rendell et al. (2017) | 8  | Isothermal          | 11                      | 90                     | Moderate            | 55                   | 22                               | 58.5           | 6      |
| Wilmott et al. (2018) A & B | 10 | Isothermal          | 10                      | 60                     | Moderate            | 47                   | 21                               | 48.7           | 6      |

* Induction method was defined as either “controlled work rate,” which was defined as a constant intensity for a set duration or “isothermal,” which was defined as exercise intensity defined by a pre-determined internal body temperature.

# Exercise intensity was defined as either “low,” which was <55% VO\textsubscript{2max}, “moderate,” which was isothermal or 55–70% VO\textsubscript{2max}, and “high,” which was >70% VO\textsubscript{2max}.

* Included four females.

* Included one female.
for time to exhaustion (Figure 3), time trial (Figure 4), mean power (Figure 5), VO\textsubscript{2max} (Figure 6), and peak power (Figure 7) were demonstrated.

**Time to Exhaustion Meta-Regression**

When all of the covariates were analyzed as individual models, induction method significantly impacted the magnitude of change seen in time to exhaustion following HA induction (coefficient [95% CI]; −0.69 [−1.01, −0.37], \( r^2 = 0.26, p < 0.001 \) (Figure 8A). Fitness level also significantly impacted the change seen in time to exhaustion, however, no variance in the results was explained by this model (coefficient [95% CI]; 0.04 [0.02, 0.06], \( r^2 = 0.00, p < 0.001 \) (Figure 8B). The heat index of testing also explained some of the variance seen in this test time (coefficient [95% CI]; 0.04 [0.02, 0.07], \( r^2 = 0.18, p < 0.001 \) (Figure 8C). All other covariates did not significantly impact the magnitude of change seen in time to exhaustion following HA (coefficient [95% CI]; induction length, 0.04 [−0.04, 0.13], \( p = 0.34 \); session duration, 0.01 [−0.00, 0.02], \( p = 0.08 \); exercise intensity, −0.27 [−0.59, 0.05], \( p = 0.10 \); heat index of induction, 0.01 [−0.01, 0.04], \( p = 0.30 \)). Of the 19 times to exhaustion tests in a hot environment, 18 saw improved performance, while one saw no changes in performance.

**Time Trial Meta-Regression**

When all of the covariates were entered as individual models, they did not significantly impact the magnitude of change seen from HA, however, high intensity training was approaching significance and this variable explained 24% of the variance seen in this type of performance test (coefficient [95% CI]; fitness level, 0.00 [−0.02, 0.03], \( p = 0.91 \); induction length, 0.08 [−0.07, 0.23], \( p = 0.28 \); session duration, 0.00 [−0.01, 0.01], \( p = 0.40 \); high intensity, −0.58 [−1.17, 0.02], \( p = 0.06 \); moderate intensity, −0.23 [−0.65, 0.18], \( p = 0.26 \); induction method, −0.08 [−0.53, 0.37], \( p = 0.74 \); heat index of induction, 0.01 [−0.02, 0.05], \( p = 0.45 \); heat index of testing, 0.03 [−0.01, 0.06], \( p = 0.16 \)). In terms of environmental conditions, time trial performance was improved in all studies, however, only one study investigated a time trial in thermoneutral conditions.
### Table 3 | Time trial descriptive table.

| References         | n   | Induction method* | Induction length (Days) | Session duration (min) | Exercise intensity* | Heat index induction | Heat index testing | Baseline fitness (ml·kg⁻¹·min⁻¹) | PEDro |
|--------------------|-----|-------------------|-------------------------|------------------------|---------------------|---------------------|--------------------|-----------------------------------|-------|
| Garrett et al. (2012) | 8   | Isothermal        | 5                       | 90                     | Moderate            | 61                  | 45                 | 65.0                             | 4     |
| Neal et al. (2016a)   | 10  | Isothermal        | 5                       | 90                     | Moderate            | 55                  | 22                 | 63.3                             | 6     |
| Guy et al. (2016)     | 8   | Controlled work rate | 7                       | N/A                    | Low                 | 50                  | 50                 | 45.0                             | 7     |
| Lee et al. (2016)     | 7   | Controlled work rate | 10                      | 60                     | Low                 | 41                  | 41                 | 50.7                             | 6     |
| Willmott et al. (2016) A & B | 7   | Controlled work rate | 2                       | 90                     | Low                 | 45                  | 33                 | 46.1                             | 6     |
| Wingfield et al. (2016) A & B | 10  | Controlled work rate | 5                       | 90                     | Low                 | 40                  | 40                 | 44.3                             | 4     |
| James et al. (2017)   | 10* | Isothermal        | 5                       | 90                     | Moderate            | 50                  | 37                 | 58.9                             | 6     |
| Pethick et al. (2019) | 24* | Isothermal        | 5                       | 90                     | Moderate            | 40                  | 38                 | 62.3                             | 6     |

*Induction method was defined as either “controlled work rate,” which was defined as a constant intensity for a set duration or “isothermal,” which was defined as exercise intensity defined by a pre-determined internal body temperature.

*Exercise intensity was defined as either “low,” which was <55% VO₂max, “moderate,” which was isothermal or 55–70% VO₂max, and “high,” which was >70% VO₂max.

* Included one female.

### Table 4 | Mean power descriptive table.

| References         | n   | Induction method* | Induction length (Days) | Session duration (min) | Exercise intensity* | Heat index induction | Heat index testing | Baseline fitness (ml·kg⁻¹·min⁻¹) | PEDro |
|--------------------|-----|-------------------|-------------------------|------------------------|---------------------|---------------------|--------------------|-----------------------------------|-------|
| Lorenzo et al. (2010) | 12  | Controlled work rate | 10                      | 90                     | Low                 | 43                  | 39                 | 66.9                             | 6     |
| Brade et al. (2013)  | 10  | Controlled work rate | 5                       | 40                     | High                | 45                  | 45                 | 55.3                             | 7     |
| Lee et al. (2016)    | 7   | Controlled work rate | 10                      | 60                     | Low                 | 41                  | 41                 | 50.7                             | 6     |
| Neal et al. (2016a)  | 10  | Isothermal        | 5                       | 90                     | Moderate            | 55                  | 22                 | 63.3                             | 6     |
| Wingfield et al. (2016) A & B | 10  | Controlled work rate | 5                       | 90                     | Low                 | 40                  | 40                 | 44.3                             | 4     |
| Wingfield et al. (2016) A & B | 10  | Controlled work rate | 5                       | 90                     | Low                 | 40                  | 40                 | 41.9                             | 4     |
| Duvnjak-Zaknich et al. (2018) | 8   | Controlled work rate | 8                       | 41                     | N/A                 | 45                  | 46                 | 54.3                             | 7     |

*Induction method was defined as either “controlled work rate,” which was defined as a constant intensity for a set duration or “isothermal,” which was defined as exercise intensity defined by a pre-determined internal body temperature.

*Exercise intensity was defined as either “low,” which was <55% VO₂max, “moderate,” which was isothermal or 55–70% VO₂max, and “high,” which was >70% VO₂max.

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**Mean Power Meta-Regression**

When all of the covariates were run as individual models, induction length significantly impacted the magnitude of change seen in mean power following HA induction (coefficient [95% CI]; induction length 0.15 [0.05, 0.25], $r^2 = 0.75$, $p = 0.002$) (Figure 9A). All other covariates did not significantly impact the magnitude of change seen in mean power from HA, however, fitness level was approaching significance and this variable explained 30% of the variance observed in this performance test (coefficient [95% CI]; fitness level, 0.03 [−0.001, 0.07], $p = 0.06$ (Figure 9B); session duration, 0.01 [−0.01, 0.02], $p = 0.36$; high intensity, −0.43 [−1.41, 0.41], $p = 0.28$; moderate intensity, −0.43 [−1.53, 0.69], $p = 0.45$; induction method, −0.23 [−1.33, 0.87], $p = 0.68$; heat index of induction, 0.00 [−0.08, 0.08], $p = 0.94$; heat index of testing, 0.01 [−0.05, 0.06], $p = 0.78$). One study that conducted a performance test in a thermoneutral environmental condition observed improved performance, while five out of the six tests that were performed in the heat saw improvements.

**VO₂max Meta-Regression**

When all of the covariates were run as individual models, they did not significantly impact the magnitude of change seen in VO₂max from HA (coefficient [95% CI]; fitness level, −0.01 [−0.02, 0.05], $p = 0.48$; induction method, −0.14 [−0.69, 0.41], $p = 0.62$; session duration, 0.00 [−0.01, 0.01], $p = 0.64$; induction length, 0.03 [−0.06, 0.11], $p = 0.54$; high intensity, −0.44 [−1.26, 0.37], $p = 0.29$; moderate intensity, −0.25 [−0.82, 0.33], $p = 0.41$; heat index of induction, −0.03 [−0.07, 0.02], $p = 0.20$; heat index of testing, −0.01 [−0.02, 0.03], $p = 0.59$). Of the nine thermoneutral VO₂max tests, eight observed improvements in performance following HA induction. Of the 12 in hot tests, seven observed performance improvements following HA induction.

**Peak Power Meta-Regression**

When all of the covariates were run as individual models, they did not significantly impact the magnitude of change seen in peak power from HA (coefficient [95% CI]; fitness level, 0.02 [−0.01, 0.05], $p = 0.22$; induction length, 0.01 [−0.08, 0.10], $p = 0.50$).
TABLE 5 | Peak power descriptive table.

| References                  | n  | Induction method* | Induction length (Days) | Session duration (min) | Exercise intensitya | Heat Index induction | Heat Index testing | Baseline fitness (ml·kg⁻¹·min⁻¹) | PEDro |
|-----------------------------|----|-------------------|-------------------------|------------------------|---------------------|----------------------|---------------------|----------------------------------|-------|
| (Castle et al., 2011) A & B | 8  | Controlled work rate | 10                      | 60                     | Low                 | 37                   | 38                  | 43.3                             | 6     |
| Brade et al. (2013)         | 8  | Controlled work rate | 10                      | 60                     | Low                 | 37                   | 38                  | 43.3                             | 6     |
| Keiser et al. (2015)        | 8  | Controlled work rate | 10                      | 90                     | Low                 | 30                   | 39                  | 61.2                             | 7     |
| Neal et al. (2016a) A & B   | 10 | Isothermal        | 5                       | 90                     | Moderate            | 55                   | 22                  | 63.3                             | 6     |
| Neal et al., 2016b A & B    | 8  | Isothermal        | 11                      | 90                     | Moderate            | 55                   | 20                  | 56.9                             | 6     |
| Rendell et al. (2017)       | 8  | Isothermal        | 11                      | 90                     | Moderate            | 55                   | 20                  | N/A                              | 6     |
| Willmott et al. (2018) A & B| 10 | Isothermal        | 10                      | 60                     | Moderate            | 47                   | 43                  | 48.7                             | 6     |

*Induction method was defined as either “controlled work rate,” which was defined as a constant intensity for a set duration or “isothermal,” which was defined as exercise intensity defined by a pre-determined internal body temperature.

aExercise intensity was defined as either “low,” which was <55% VO₂max, “moderate,” which was isothermal or 55–70% VO₂max, and “high,” which was >70% VO₂max.

$p = 0.77$; session duration, 0.00 [−0.01, 0.02], $p = 0.40$; high intensity, −0.24 [−1.02, 0.54], $p = 0.54$; moderate intensity, −0.27 [−0.77, 0.22], $p = 0.28$; induction method, −0.19 [−0.61, 0.22], $p = 0.36$; heat index of induction, −0.02 [−0.04, 0.003], $p = 0.09$; heat index of testing, 0.01 [−0.01, 0.03], $p = 0.56$). Peak power performance improved in all tests, regardless of testing environmental conditions (thermoneutral, $n = 4$; hot, $n = 6$).

**DISCUSSION**

The largest performance improvement was observed in time to exhaustion include lower internal body temperature (at baseline and during exercise) and heart rate that occur over the course of HA. The second largest magnitude of improvement was observed in time trials (MD, −45.6 s), followed by mean power (MD, 12 W), VO₂max (MD, 1.32 ml·kg⁻¹·min⁻¹), and peak power (MD, 15 W). Previous research demonstrated a 7% improvement in performance tests following HA (Tyler et al., 2016). These performance improvements following HA were most likely due to decreases in maximal cardiac output, lactate threshold and plasma volume, lowered skin temperature and a larger core-to-skin gradient as seen in previous research (Périard et al., 2015). However, VO₂max might be impacted through improved fitness induced by exercise training alone compared to HA specifically (Brooks et al., 2015). Finally, peak power is not specifically a measurement of aerobic performance, thus, might not be impacted as substantially as other tests from HA.

One potential moderator that could explain some of the variance between studies that could not be accounted for in this analysis is the number of days of rest following HA before testing. There were a wide variety of reporting methods for the metric that does not allow for certainty in this analysis. For example, many manuscripts reported completing the performance test “within x number of days,” meaning some participants may have completed the test the day after HA induction and other participants may have completed the test on day x after the end of HA induction. In general studies reported completing the tests anywhere from one to seven days following HA induction. A recent paper by Daanen et al. demonstrated that internal body temperature was lowered three and seven days following HA induction compared to the day immediately following HA induction. Thus, leading one to believe that performance adaptations may also be improved with a few days of recovery following HA induction, however, future research is needed (Daanen et al., 2011). Another meta-analysis has extensively examined the timeline of HA decay and concluded that internal body temperature and heart rate responses typically
decay at a rate of 2.5% per day (Daanen et al., 2018). The importance of recovery has even been examined and reported when seeking optimal training improvements in a thermoneutral environment and 96 h of rest following training was suggested (Waldron et al., 2019). The results from both of these manuscripts point to the importance of finding the appropriate balance between recovery and acclimation decay for optimal performance results.

While differentiating the performance outcomes between HA and training alone is of importance, the current analysis did not examine these differences. Of the manuscripts included in this analysis, only 11 included a control group (time trial, n = 5; time
to exhaustion, $n = 4$; $\text{VO}_{2\text{max}}, n = 6$; peak power, $n = 3$; mean power, $n = 2$). HA appears to improve time trial performance compared to controls (Guy et al., 2016; Lee et al., 2016; Willmott et al., 2016; James et al., 2017). One short term HA protocol (4–6 days) did not elicit statistically significant improvements in time trial performance compared to a control group, however, moderate to large effect sizes were reported (Willmott et al., 2016). Time to exhaustion improved with HA in all studies, but not with control groups (Nielsen et al., 1993; Chen et al., 2013; James et al., 2017; Willmott et al., 2018). In terms of $\text{VO}_{2\text{max}}$, the performance differences between HA and training are unclear, as some studies reported differences between the groups and other did not (Lorenzo et al., 2010; Chen et al., 2013; Keiser et al., 2015; James et al., 2017; Rendell et al., 2017; Willmott et al., 2018). Peak power may improve with HA compared to training alone, however, the results are unclear and future research is...
needed (Keiser et al., 2015; Rendell et al., 2017; Willmott et al., 2018). Both studies that assessed mean power demonstrated improved performance benefits from HA compared to a control group (Lorenzo et al., 2010; Lee et al., 2016). To determine the true performance changes of HA compared to training alone, future studies should aim to include a control group within their study design.

**Time to Exhaustion**

As previous research has clearly established, HA is an effective strategy to improve time to exhaustion and this was evident in the current meta-analysis, as no study reported decrements. The study that observed the largest performance improvement (ES = 8.98) took place with the participants who held the highest VO$_{2max}$ (62.0 ml·kg$^{-1}$·min$^{-1}$), hypothetically giving them a higher training ceiling (Nielsen et al., 1993; Chen et al., 2013; James et al., 2017; Willmott et al., 2018). The HA induction took place over the course of 10 days for $\sim$48 min per session at a low exercise intensity (120 beats per minute; $\sim$45% VO$_{2max}$) and in the most extreme environmental conditions (ambient temperature, 35.4 ± 0.05°C; relative humidity, 87.2 ± 0.04%) of any study included in this analysis (Nielsen et al., 1997). Pandolf et al. also observed large improvements in time to exhaustion following HA (ES = 3.88) with a controlled work rate exercise intensity for 150 min over 10 days in relatively fit, middle-age individuals (VO$_{2max}$ = 52.9 ml·kg$^{-1}$·min$^{-1}$) (Pandolf et al., 1988). The purpose of this particular research was to examine differences in young and middle age males over the course of HA who were matched for several morphological factors and the magnitude of performance time change was much larger for the younger group than the middle age group, due to the younger group reaching exhaustion much sooner than the middle age group at the beginning of HA, however, the middle-age group was not included in this analysis since their baseline test did not meet the inclusion criteria (Pandolf et al., 1988). The authors of this study hypothesized that the higher training volume of the middle aged men explained their thermoregulatory advantage at the beginning of HA, as they reported running on average 20 more miles per week than the younger men, pointing to the importance of previous training for improved thermoregulation capabilities (Pandolf et al., 1988). Despite this difference, HA induction successfully allowed the younger men to reach the same thermoregulatory capacity as middle aged men (Pandolf et al., 1988).

Two studies included in this meta-analysis did not observe any time to exhaustion performance improvements following HA induction (Pandolf et al., 1988; Aoyagi et al., 1998). One potential explanation of these findings in one of these studies is the low exercise intensity of the test (walk at 1.34 m·s$^{-1}$ to exhaustion), allowing participants to complete the test to completion before HA induction ensued (Aoyagi et al., 1998). Similarly, the other group in the Pandolf et al. study was able to tolerate the test well on the first day of HA, most likely due to their training history (Pandolf et al., 1988).

Of the moderators entered into the meta-regression, induction method and fitness level appear to explain some of the variance seen in this type of performance test following HA. Controlled work rate exercise intensity during HA appears to hold a slight advantage over isothermal (controlled work rate ES = 1.00; isothermal ES = 0.31). One possible mechanism to explain this finding is the potential increase in area under the heating curve with controlled work rate exercise intensity during HA, as the isothermal method might actually lead to a lower overall thermal load since the exercise is adjusted to maintain a temperature of 38.5°C (Bardis et al., 2013).

While recent evidence suggests that peak internal body temperatures of 39°C are not more advantageous than the traditional isothermal temperature of 38.5°C (Gibson et al., 2015b, 2019), there are perhaps greater improvements with increased levels of hyperthermia (>39.0°C), especially in elite level athletes. Data from the Union Cycliste Internationale Road...
Cycling World Championship demonstrated the capability of elite level athletes to tolerate internal body temperatures well above what is often reported in the HA literature (as high as 41.5°C), however, future research is needed in this area. An increased thermal load has the potential to drive HA through several mechanisms, including, an increased cardiac response, skin temperature, and sweat rate (Shibasaki et al., 2006; Périard et al., 2016). While increased internal body temperature has the potential to elicit greater HA adaptations, a valid measure of internal body temperature (ingestible thermistor or rectal temperature) and professionals trained in recognizing and treating exertional heat illness is needed when intentionally inducing HA in this way to ensure athlete safety.

Fitness level also appeared to impact the results seen in this performance test, as studies with higher starting VO_{2max} values appeared to have greater improvement in this type of performance test. For example, an individual with a VO_{2max} of 60 ml·kg^{-1}·min^{-1} (predicted ES = 1.50) is likely to achieve a larger magnitude of performance changes following HA compared to an individual with 40 ml·kg^{-1}·min^{-1} (predicted ES = 0.7). Because of the stimulation of sweating and skin blood flow (Piwonka et al., 1965), improved evaporative cooling (Gisolfi and Robinson, 1969), greater cardiac stability (Strydom and Williams, 1969), changes in fluid dynamics (Senay, 1979), earlier onset of sweating (Baum et al., 1976; Nadel, 1979), and greater sweat sensitivity (Wells et al., 1980), aerobically trained individuals appear to show partial HA benefits (Armstrong et al., 1987).

**Time Trial**

Time trial performance is arguably the most applicable in the sport setting and every study included in this meta-analysis demonstrated faster times following HA induction. Time trial was improved by −0.76 min on average. Garrett et al. saw the largest improvement in time trial performance (ES =1.50) following HA using the isothermal method for 90 min over 5 days in participants holding the highest VO_{2max} (65.0 ml·kg^{-1}·min^{-1}) in the most extreme environmental conditions (ambient temperature, 39.5°C; relative humidity, 60%). A previous review by Périard et al. demonstrated aerobically fit individuals can develop adaptations to HA rapidly (Périard et al., 2015). Lee et al. also demonstrated large improvements following HA induction (ES =1.42) (Lee et al., 2016). The HA induction took place with a controlled work rate for 60 min over the course of 10 days with relatively fit individuals (VO_{2max} = 50.7 ml·kg^{-1}·min^{-1}). Willmott et al. showed the smallest improvements following HA with 30 min of exercise at a high intensity controlled work rate for 5 days in 32°C and 60% relative humidity (ES = 0.002). Previous research suggested 60–120 min of exercise duration to induce optimal adaptations following HA, therefore, 30 min of exercise for each session in this study might not be enough to elicit optimal adaptations (Sawka et al., 2011).
Of the moderators entered into the meta-regression, exercise intensity might explain some of the variance (24%) seen in this type of performance test following HA even though it was not significant. Low intensity exercise induced large adaptations in time trial performance (High intensity, ES = 0.00; Moderate intensity; ES = 0.35; Low intensity, ES = 0.58), which could be due to lower levels of fatigue from HA that might be seen with high or moderate exercise intensity.

**VO$_{2\text{max}}$**

It has been well-established that fitness level contributes substantially to someone's ability to thermoregulate and that individuals with higher fitness levels already demonstrate some
physiological parameters of HA (Pandolf et al., 1977). One interesting phenomenon that is evident from this meta-analysis is that there are also improvements of VO$_{2\text{max}}$ following HA induction. Keiser et al. observed a 9.6% improvement in VO$_{2\text{max}}$ following 10 days of 90 min low intensity HA sessions (Keiser et al., 2015). Lorenzo et al. also demonstrated large improvements in VO$_{2\text{max}}$ following 10 days of 90 min, low intensity HA sessions (MD ± SD, −4.5 ± −0.5 ml·kg$^{-1}$·min$^{-1}$) (Lorenzo et al., 2010). VO$_{2\text{max}}$ was lower following HA in eight studies, unlike time to exhaustion and time trial performance tests that did not demonstrate any negative outcomes following HA.

There are several factors that could help explain these negative findings, including the fatigue, training impulse, and the participant’s starting fitness levels. Similar to any novel training, HA introduces new stress to the body and can lead to fatigue. Daanen et al. recently demonstrated further performance improvements following HA when a break was initiated at the cessation of induction prior to the performance test (Daanen et al., 2011), allowing the participants time to recover and reap the full benefits of HA. Aoyagi et al. demonstrated the largest decrement in VO$_{2\text{max}}$ following HA (MD ± SD, −1.4 ± −0.4 ml·kg$^{-1}$·min$^{-1}$), that involved 150 min (longest exercise duration) of 12 days of HA with only one rest day (Aoyagi et al., 1998). Similarly, Febbraio et al. saw decrements in VO$_{2\text{max}}$ following HA induction (MD ± SD, −1.5 ± −0.6 ml·kg$^{-1}$·min$^{-1}$) in highly fit participants, however, the test took place within 24 h of the final HA session, which might not have allowed the full adaptations to take place (Febbraio et al., 1994). There were no moderators that largely impacted the magnitude of changes seen in VO$_{2\text{max}}$.

**Power**

Power is another critical performance measurement that can be applicable in sport settings. In this meta-analysis, mean power and peak power were analyzed. Mean power was improved by 12 W, on average. Lorenzo et al., reported the largest improvements following HA (Lorenzo and Minson, 2010). HA induction took place with 90 min of low intensity, controlled work rate for 10 days at 40°C and 30% relative humidity. Duvnjak-Zaknich et al. also showed large improvements following HA in mean power (ES = 0.480), in which the HA induction took place with 41 min of controlled work rate exercise for 8 days at 35°C and 60% relative humidity (Duvnjak-Zaknich et al., 2018). Lee et al. also showed large improvements in mean power (ES = 0.467). However, Wingfield et al. demonstrated negative mean power result following 30 min of high intensity controlled work rate HA for 5 days and the smallest improvement following 90 min of low intensity control work rate for 5 days in 33°C and 60% relative humidity (Wingfield et al., 2016). The studies showing larger improvements achieved longer length of HA induction. In addition to this point, Wingfield et al. measured mean power during five times of 6 s sprints, while other studies performed mean power during aerobic exercise test, such as 60 min exercise. HA induction could be more beneficial to improve mean power during aerobic exercise following longer duration of induction length.

Induction length explained 75% of the variance seen in power output following HA. For example, when HA induction length was 10 days, the predicted magnitude of change was ES = 0.86 and when it was 5 days, the predicted magnitude of change was only ES = 0.11. This finding is in line with original research which pointed to the full adaptations of HA taking 10 days (Armstrong and Maresh, 1991). However, these findings should be interpreted with caution, as there were only seven studies included in this analysis and other variables, such as the participant's previous training history, were not accounted for and could contribute to this variability. In fact, fitness level was approaching statistical significance in the regression model and may contribute to the variability with increased statistical power.

Peak power was improved 15 W, on average. Keiser et al. showed the largest improvements (ES = 1.695) which took place with 90 min of low intensity exercise for 10 days in 33°C and 39% relative humidity, while other studies showed smaller improvements following HA (ES = 0.030–0.339). Peak power was measured during a graded exercise test, repeated short sprint test, and longer duration exercise. There were no moderators that significantly impacted the results seen in peak power, most likely due to this type of test not directly measuring aerobic capacity, but more likely anaerobic capacity.

**Limitations**

While the goal of this meta-analysis was to provide an overview of various performance tests, this meta-analysis was not without limitations. One limitation of this meta-analysis was that some papers did not report correlations which was necessary to calculate ES in the statistical software. In this case, the lowest correlation value was used to achieve the most conservative outcomes. Even though females were included in this analysis, it is unclear if the current findings can be extrapolated to this population due to the variety of or lack of control over menstrual cycle status. For example, one study did not control for menstrual cycle status and simply reported that the findings were not different when females were excluded from the analysis (Pethick et al., 2019). Another study reported completing pre-tests and HA during the follicular phase of the menstrual cycle and post-tests during the luteal phase (James et al., 2017). Still, some did not report information about menstrual cycle status (Horstman and Christensen, 1982; Ashley et al., 2015). A further limitation of this meta-analysis was that each type of performance test had slightly different testing methods. For example, the distance of the time trial was not the same among the studies but were still categorized as a time trial. The moderator analysis may help with the interpretation of these results. While the physiological mechanisms behind power, endurance, and sprint tests cannot be understated, there were not enough peak power and mean power studies to utilize these categories as moderators in the current analysis. Another limitation was when data needed to calculate effect size was not reported in text or tables and it was demonstrated in figures, the data was estimated using a ruler. Additionally, while all studies reported the use of internal body temperature assessment, very few reported the actual internal body temperature data during HA induction and this meta-analysis could not include this information as a moderator.
However, a previous review indicated an increased internal body temperature during HA is a critical factor to induce adaptations (Périard et al., 2015). Future research should ensure that the internal body temperature data during the HA sessions are reported.

CONCLUSIONS AND PRACTICAL APPLICATION

A wide range of HA induction protocols have been investigated in this meta-analysis. The largest performance improvement was observed in time to exhaustion followed by time trial, mean power, VO$_{2\text{max}}$, and peak power following HA. The results observed in these performance tests were each impacted differently by specific moderators. Performance enhancements were greater in time to exhaustion tests when a controlled work rate method was utilized for HA and when the participants of these studies began the HA with higher baseline fitness levels, as indicated by VO$_{2\text{max}}$. Time trial results were improved if the HA induction involved low exercise intensity, which could be related to the participants in these studies not experiencing fatigue from high intensity HA. Longer HA induction (i.e., 10 days) appeared to elicit greater adaptations in mean power than short HA induction (i.e., 5 days). Sport scientists and researchers can use the findings from this meta-analysis to customize the design of HA induction protocols to maximize the adaptations of specific performance tests.

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AUTHOR CONTRIBUTIONS

CB and YS developed the idea of the meta-analysis, completed the analysis, and created the figures. CB, YS, and LF worked to review and code all of the manuscripts. LF created the tables. DC verified the manuscript review and analytical methods. All authors reviewed and edited the manuscript.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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