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Title

Thermal stress in North Western Australian iron ore mining staff

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Running Header

Thermal safety in Western Australian mining staff

Abstract

Introduction: Demand for Australian mined iron ore has increased employment within this sector thus exposing increased numbers of workers to the harsh Australian climate. This study examined the influence of hot (>30^{o}C WBGT) environmental temperatures, consistent with working in North Western Australia, on iron ore mining staff. **Methods:** Core temperature, hydration status, perceived exertion, mood and fatigue state were measured in 77 participants at three time points (pre-, mid-, and post-shift) during a normal a 12-hour shift at an open cut iron ore mining/processing site (N= 31; Site$_1$) and an iron ore processing/shipping site (N= 46; Site$_2$). **Results:** A significant effect for time was observed for core temperature with greater mean core temperatures measured mid- (37.5 ± 0.4^{o}C) and post-shift (37.6 ± 0.3^{o}C) compared with pre-shift values (37.0 ± 0.5^{o}C). All mean core temperature measures were below ISO7933 thresholds (38^{o}C) for thermal safety. Mean hydration measures (Urine Specific Gravity; USG) were greater at Site$_1$ (1.029 ± 0.006) compared with Site$_2$ (1.021 ± 0.007). Furthermore, both pre- and post-shift measures from Site$_1$ and post-shift measures from Site$_2$ were greater than the threshold for dehydration (USG = 1.020). No differences were observed for mood or perceived exertion over time; however, measures of fatigue state were greater post-shift compared with pre- and mid-shift values for both sites. **Conclusions:** Our findings indicate that while the majority of mine workers in North Western Australia are able to regulate work-rate in hot environments to maintain core temperatures below ISO safety guidelines, 22% of workers reached or exceeded the safety guidelines, warranting further investigation. Furthermore, hydration practices, especially when off-work, appear inadequate and could endanger health and safety.

Key words: Safety, Heat, Hydration, Core Temperature, Thermal Work Limits

Introduction

Working in hot and humid environments presents unique challenges to both performance and occupational health and safety. Physical exertion under hot environmental conditions (ambient temperatures >30^{o}C) is associated with a significant increase in the perception of effort (Tucker, 2009) and a decrease in physical work capacity (Abbiss and Laursen, 2005; Peiffer et al., 2010; Tucker et al., 2004). For example, Gonzalos-Alonzo (1999) observed a significantly shorter time to fatigue during constant paced exercise in the heat (40^{o}C), compared with a cooler condition (18^{o}C). In addition, if left unchecked, rises in core temperature during exposure to heat can increase the risk of heat related illnesses (Brake and Bates, 2002; Casa and Roberts, 2003; Smalley et al., 2003). In an industrial setting, an increase in thermal-induced fatigue and decrease in mental arousal (Nybo and Nielsen, 2001) could increase the probability of worker injury. Individuals working in the mining industry in North Western Australia are increasingly susceptible to heat related injury and illness as ambient temperatures in this region can be in excess of 30^{o}C WBGT (wet globe bulb temperature, which is a measure for the effects of temperature, humidity, wind and solar radiation on the organism) for extended periods. Therefore, understanding the influence of hot environmental temperatures on worker physiology is essential in order to implement effective strategies to enhance worker safety.

Surrogate parameters, such as the WGBT, are often used as indirect heat stress indices and the primary indicator of thermoregulatory stress in occupational settings. Nevertheless, the efficacies of many of the existing heat stress indices have been questioned due to poor development or limitations in practicality and/or application (Brake and Bates, 2002). For this reason, Brake and Bates (2002) developed the Thermal Work Limit (TWL), a calculation of the maximal metabolic work rate possible for an acclimatised, euhydrated worker under various heat stresses (e.g. ambient temperature and WGBT) in order to maintain a safe deep body core temperature < 38.2^{o}C. The use of TWL has been validated in a laboratory setting (Brake and Bates, 2001) and in underground miners (Miller and Bates, 2007), and has been suggested to be superior to the widely used WBGT which can result in an overly conservative approach to worker safety (Brake and Bates, 2002). The validation of TWL in above ground workers is lacking. Bates and Schneider (2008) examined TWL in United Arab Emirates (UAE) workers; however, this study used tympanic temperature as the criterion for core temperature. Tympanic temperature can misrepresent core temperature as a mean bias of 1.0^{o}C has been observed when using tympanic temperature compared with rectal temperature in human participants (Casa et al., 2007). For this reason, validations of TWL in above ground workers under thermal stress are needed.

With a greater world reliance on Australia mined iron ore and the lack of adequate information available in relation to individuals working in these environments, the purposes of the present study were to: i) examine the core temperature, hydration status and perception of fatigue, mood and exertion in individuals working above ground at both mining/processing and processing/shipping sites under thermally hostile environments, and ii) assess the efficacy of TWL in this group, and iii) examine differences in individuals responses to working in hot conditions.

Methods

Participants

Seventy-seven males volunteered to participate in this study. Of the 77 participants, 31 individuals (age: 34.4 ± 10.3 years; height: 178.6 ± 7.9 cm) were working as iron ore mining/processing staff at an open cut mine located in North Western Australia ($Site_1$) while the remaining 46 individuals (age: 35.2 ± 11.5 years; height: 176.2 ± 9.6 cm) were working at a North Western Australia processing/shipping port ($Site_2$). Participants were selected based on their risk of exposure to high environmental temperatures; thus all participants worked in manual labour positions that required prolonged daily exposure (approximately 10 hours) to outdoor conditions. In addition, at the time of data collection (January – March) all participants had been employed in their current position at this site for greater than three months; thus these individuals were considered heat acclimatised (Gill and Sleivert, 2001). Participants were provided with the risks and benefits of participation in this study and a signed informed consent was obtained prior to data collection. This study was approved by the Human Research Ethics Committees at Edith Cowan University and Murdoch University prior to start of data collection.

Procedures

Participants were required to work a normal 12 hour shift (6.00am to 6.00pm) and instructed not to complete additional tasks not normally required within their job duties. All data for each site were collected over a period of five consecutive days (between the months of January – March) under hot and humid (mean conditions for both sites: ambient temperature: 33.8 ± 2.6^{o}C, relative humidity: 38.1 ± 14.8%, WBGT: 30.7 ± 2.6^{o}C; Table 1) environmental conditions. Two hours before the start of the 12 hour shift, participants were instructed to ingest a radiotelemetric core temperature pill (HQinc, Florida, USA) for the measurement of internal body temperature. Immediately before the 12 hour shift, hydration status was measured from a urine sample (see below), core temperature was recorded, body mass was measured and levels of fatigue (1 – 10; 10 = very fatigued) and mood state (1 – 10; 10 = great mood) were measured using a 10 point-scale. Mid-shift (12.00pm), participants reported to a designated area where core temperature, self-reported fluid intake, ratings of perceived exertion (RPE; 1 – 10 scale; 10 = great deal; (Borg, 1982)), mood and fatigue state, and body mass were measured. Immediately after the completion of the 12 hour work shift the complete battery of measurements were again obtained.

Thermal Work Limits

Hourly (6.00am to 6.00pm) data for ambient temperature, humidity, and wind speed were obtained from the Australian Bureau of Meteorology for each testing day. Using technique previously describe by Brakes and Bates (2002) mean TWL were calculated for each work day using the mean ambient temperature, humidity and wind speed. In addition, TWL were calculated for a condition of zero wind, as many participants worked within workshops that allowed negligible wind flow within their work areas (Table 1).

Hydration Status

Pre- and post-work urine specific gravity (USG) were measured using a handheld refractometer (Nippon Optical Works, Japan) with a USG recording greater than 1.020 defined as dehydrated (Casa et al., 2000). In addition, changes in body mass (pre-shift – post-shift) and self-reported fluid intake (L) were used to indicate the participants' ability to match sweat loss with fluid consumption. Body mass was measured using a portable electronic scale (Taylor model 7506; USA) with an accuracy of ±0.1kg. Furthermore, body mass was always measured wearing the same clothing pre- and post-shift and following voiding the bladder.

Statistical Analysis

Difference in core temperature, hydration status, perceived fatigue, mood, and effort during the 12 hour work shift (pre-shift, mid-shift, and post-shift) between sites were analysed using a two way variance analysis (ANOVA; site x time) with repeated measures. Significant main effects or interactions were analysed using Tukey's HSD post-hoc analysis. Mean core temperature data from each site, at each measured time point, were analysed against the International Safety Organisation (ISO) guidelines for core temperature thermal safety ($38^{o}C$; ISO7933 (International-Standards-Organization, 2004)) using a single value T-test with Bonferroni corrections for multiple comparisons. In addition, a similar analysis was completed for mean USG values against the pre-defined USG (1.020) consistent with dehydration (Casa, Armstrong, Hillman, Montain, Reiff, Rich, Roberts and Stone, 2000). All statistical analyses were completed using Statistica data analysis software (Version 7; StatSoft, USA) with the level of significance set to $p \leq 0.05$. Data are presented as mean ± standard deviations.

Results

Mean environmental conditions for $Site_1$ and $Site_2$ during the monitoring periods are summarised in Table 1. Mean ambient temperature was greater at $Site_1$ (35.3 ± 1.9°C) compared with $Site_2$ (31.5 ± 2.1°C; $p<0.01$); conversely, mean relative humidity was lower at $Site_1$ (30.9 ± 11.5%) compared with $Site_2$ (47.1 ± 13.4%; $p=0.02$). No differences were observed for WGBT, TWL with wind, or TWL without wind between sites.

A significant main effect for time ($p<0.01$) was observed for core temperature in both sites with higher core temperatures recorded mid- ($p<0.01$) and post-shift ($p<0.01$) compared with pre-shift values (Figure 1). Furthermore, mid- and post-shift core temperatures at $Site_1$ (37.5 ± 0.4°C and 37.6 ± 0.2°C; respectively) and $Site_2$ (37.5 ± 0.4°C and 37.6 ± 0.3°C; respectively) were lower ($p<0.05$) than the ISO suggested threshold for core temperature (38°C; ISO7933 (International-Standards-Organization, 2004)). Examination of the individual subjects' data indicated that throughout the day a total of 4 participants were above the ISO suggested threshold for core temperature at Site 1 and 5 participants at Site 2 (Figure 1).

A significant main effect for site ($p<0.01$) was observed in USG measures with a higher mean USG measured in $Site_1$ (1.029 ± 0.006) compared with $Site_2$ (1.021 ± 0.007) (Figure 2). Furthermore, mean pre- ($p<0.01$) and post-shift ($p<0.01$) USG measures recorded from $Site_1$ and post-shift ($p<0.01$) measures recorded from $Site_2$ were greater than the pre-determined USG threshold for dehydration (1.020; (Casa, Armstrong, Hillman, Montain, Reiff, Rich, Roberts and Stone, 2000)). Examination of the individual subjects' data indicated that throughout the day USG was above 1.020 in a total of 28 participants at Site 1 and 29 participants at Site 2 (Figure 2). Changes in body mass and self reported fluid intake for each site are highlighted in Table 2. No differences were observed for body mass between sites (p=0.95) or over time (p=0.98) (Table 2). Self reported fluid intake showed a main effect for time (p=0.03) with 0.4 ± 1.3 L (data pooled for $Site_1$ and $Site_2$) greater fluid intake measured in the morning (i.e. pre to mid shift) compared with the afternoon (mid to post shift).

Ratings of perceived exertion, mood and fatigue state are outlined in Table 3. No differences were observed for perceived exertion or mood state between sites (p=0.20 and p=0.92; respectively) or over time (p=0.66 and p=0.24; respectively). A significant (p<0.01) main effect for time was observed for fatigue with greater levels of fatigue measured post-shift compared with pre- (p<0.01) and mid-shift (p<0.01) values.

Discussion

The purpose of this study was to examine the influence of working in a thermally hostile environment on core body temperature, hydration status, perceived exertion, fatigue, and mood state in above ground iron ore mining staff in North Western Australia. The main findings from this study were: i) a significant increase in core temperature was observed over time; however, mean core temperature did not exceed ISO safety standards, and ii) overall, hydration status was considered poor with USG values measured above dehydration thresholds for both sites.

In the iron ore mining sector, the typical demands associated with manual labour increase the risk of injury (Bhattacherjee et al., 2007). Furthermore, in many Australian mines, it is not uncommon for mining staff to work in thermally hostile conditions (WGBT>30^{o}C). These workers must not only be aware of the inherent dangers of their occupation but also the dangers imposed by the environment. In our participants, working in hot ambient temperatures (Table 1) resulted in a significant increase in core temperature during the 12 hour work shift (Figure 1). Nevertheless, the increase was relatively small (0.6 ± 0.5^{o}C) with the greatest increase observed from pre- to mid-shift (0.5 ± 0.5^{o}C; 6 hours) with only a further increase of 0.1 ± 0.4^{o}C observed mid- to post-shift (6 hours). The highest core temperature averaged over all participants in the present study (~37.6^{o}C) was below temperatures commonly associated with negative side effects (Nybo and Nielsen, 2001; Tucker, Rauch, Harley and Noakes, 2004; Yeo, 2004) and significantly below the ISO suggested threshold for core temperature (38^{o}C; ISO7933 (International-Standards-Organization, 2004). These findings may be taken to suggest that the nature of work completed by the mine processing staff involved in this study does not result in dangerous high core temperatures, even when working in a hot environment. However, our observed changes in mean core temperature does not discount the need for caution as several individual workers did present with core temperature measurements in excess of ISO safety standards (International-Standards-Organization, 2004) (Figure 1). Indeed, a 17 of 77 (22%) participants in the present study reached or exceeded the ISO safety standards for core body temperature. Further, it is possible that certain circumstances, not monitored in this study (e.g. confined space work and natural circadian rhythms in core temperature), could increases the risk of developing dangerously high core temperatures. For instance, core temperature increases in a rhythmic manner (Drust et al., 2005) with peak core body temperatures observed late in the day. Such natural circadian changes in temperature coupled with unusually high work-rates or working in confined non-ventilated spaces could result in significant number of workers exceeding ISO guidelines. Further studies providing continuous monitoring of core temperature changes during various mining activities are therefore warranted.

The moderate core temperatures observed in this study were not completely unexpected despite WGBT temperatures in excess of 30^{o}C. Current ISO7243 guidelines have identified a WGBT of 30^{o}C as a threshold leading to a significant reduction in work performance and as a temperature warranting greater break frequency during work periods (International-Starndards-Organization, 1989). Nevertheless, in our participants, working in conditions >30^{o}C WGBT (Table 1) did not result in dangerously high core temperatures. As workers are able to self-select their work rate, it is possible that prolonged exposure to the high environmental temperatures resulted in a down-regulation of work intensity (Hanna et al., 2011; Tucker, Rauch, Harley and Noakes, 2004). Supporting this, ratings of fatigue recorded in the afternoon/evening (i.e. post-shift) were significantly greater compared with morning values (i.e. pre- and mid-shift; Table 3). This higher perception of fatigue later in the day would have resulted in a decrease in work-pace (Tucker, Rauch, Harley and Noakes, 2004), resulting in the attenuated increase in core temperature observed in the later part of the day (Figure 1). Our findings indicate that using WGBT as an indicator of thermal stress in above ground mining staff may result in an overly cautious approach to worker safety. Alternatively, thermal indices that incorporate greater environmental and physiological data (i.e. wind speeds, clothing insulatory capacity, and sweat rates) can provide more accurate depictions of thermal stresses that workers may encounter. Indeed, mean TWL, when calculated with wind, were greater than 140 $W*m^{-2}$ for both sites during the collection period, with few limitations to work rate or frequency suggested at these levels (Brake and Bates, 2002). Conversely, mean TWL calculated without wind was considerably lower (110 to 116 $W*m^{-2}$), indicating that participants would be required to have regular breaks and would have limited capacity to do work. Since average core body temperatures in the present study were within safe work limits, these results indicate that TWL calculated with wind may provide a more realistic thermal stress index, compared with WGBT or TWL calculated without wind flow. However, it should be noted that these indices of thermal strain were calculated based upon the environmental conditions (i.e. temperature, humidity and wind speed) of each individual mining site. Since many mining tasks involve working in confined areas which create microclimates with minimal or limited wind flow further work is required in order to understand the appropriateness of WGBT and TWL (with and without wind flow) as indices of thermal strain when accounting for environmental conditions experienced by each individual employee.

Working in hot environmental conditions can place a large strain on an individual's body as the need to cool the core results in high sweat rates (Donaldson et al., 2003). Without proper hydration, prolonged sweating can lead to a decrease the total volume of water stored within the body and can acutely decrease performance, alter mental states (Casa, Armstrong, Hillman, Montain, Reiff, Rich, Roberts and Stone, 2000), and lead to syncopy (Binkley et al., 2002). For this reason, adequate hydration practices are paramount when working in hot environmental conditions and are a priority in most Western Australian mining operations. Despite a large educational program within the two monitored sites, our data indicates that most mining staff start and finish work in a state at, or above dehydration thresholds (Figure 2). Interestingly, fluid intake during work hours was adequate to maintain body mass thus, indicating that workers are able to judge their sweat rate and ingest fluid at an appropriate level. It should be noted however that the clothing worn by participants during post exercise measurements may have held some water/sweat therefore resulting in an underestimation of body weight loss. Despite this, the high USG at commencement of work indicates that participants in the present study adopted inadequate hydration practices outside of work, during workers' 'off-time'. These findings are not novel and have been observed in a study by Brake and Bates (2003). Interestingly, we also observed a significant difference in the level of hydration (USG) between the two sites monitored in this study. Although core temperature changes, weight loss, fluid intake and WGBT during work were similar between the sites, it is possible that the higher ambient temperature observed in Site 1 was responsible for the greater dehydration observed at Site 1. Clearly, further research is warranted in order to better understand 'off-time' practices of workers and factors influencing hydration status, especially with regards to work in varying environmental conditions.

The results of the present study provide useful information on the thermal stresses experience by Western Australian open cut mining staff; however, we do acknowledge limitation in our data collection that may have affected our findings. Without an actual measure of physical activity it is not possible to quantify changes in self-selected work rate that may have occurred during prolonged exposure to the high environmental temperatures. Nevertheless, as ratings of fatigue increased over time while rating of perceived exertion remained stable (Table 3), it is logical to suggest that work rate would have decreased. Indeed, a decrease in self-selected work rate under hot environmental conditions has previously been observed in high-intensity exercise-based research (Peiffer and Abbiss, 2011; Tucker, 2009). Additionally, our hydration measures incorporated a self-reported fluid intake which can be prone to over, or underestimation (Westerterp and Goris, 2002). Regardless, as all staff were accustom to using the designated fluid delivery mechanisms, we are relatively confident that the reported fluid intake was accurate.

Conclusion

An increased demand for Australian iron ore has resulted in an Australian mining boom, with increased numbers of individuals finding work within this sector. For this reason, mining companies, and workers alike, need to be aware of the inherent dangers of working in the heat. Our findings indicate that albeit working in a hot environment (WGBT > 30 °C), open cut mining staff in North Western Australia are able to self-regulate work intensity to maintain relatively safe internal body temperatures. Nevertheless, hydration strategies while sufficient during work hours are not adequately being addressed after hours, which could present safety issues. Although mining companies provide sound education to workers with regard to all aspects of safety, it is suggested that education on thermal stress, specifically 'at home' or off-duty hydration practices, should be increased to help minimise the possibility of heat related illness and accidents.

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Tables

Table 1. Ambient Temperature (^{o}C), humidity (%), WGBT (^{o}C), and thermal work limits with (TWL_w) and without (TWL_{wo}) air flow measured over three days at an above ground iron ore mining/processing site ($Site_1$) and at an iron ore processing/shipping port ($Site_2$) in North Western Australia.

	Ambient Temperature	**Relative Humidity**	**WGBT**	**TWL_w**	**TWL_{wo}**
$Site_1$	35.1 ± 1.8[a]	29.9 ± 10.7	30.5 ± 1.7	140.5 ± 9.5	109.7 ± 10.7
$Site_2$	31.5 ± 2.1	50.4 ± 11.2[b]	30.9 ± 3.8	146.5 ± 21.5	116.0 ± 19.3

[a] $Site_1$ significantly greater compared with $Site_2$; [b] $Site_2$ significantly greater compared with $Site_1$

Table 2. Body mass (kg) measured pre-shift (Pre), mid-shift (Mid), and post-shift (Post) and self reported fluid intake (L) pre- to mid-shift and mid- to post-shift during a normal work period at an above ground iron ore mining/processing site ($Site_1$) and at an iron ore processing/shipping port ($Site_2$).

	Body mass			**Fluid intake [a]**	
	Pre	**Mid**	**Post**	**Pre to Mid**	**Mid to Post**
$Site_1$	91.8 ± 13.9	92.2 ± 13.7	91.5 ± 13.8	1.8 ± 1.2	1.5 ± 0.8
$Site_2$	92.3 ± 17.8	91.3 ± 17.2	91.9 ± 17.8	1.7 ± 1.3	1.3 ± 0.8

[a] Main effect for time: post-shift<mid-shift values.

Table 3. Fatigue, mood, and ratings of perceived exertion (RPE) measured pre-shift (Pre), mid-shift (Mid), and post-shift (Post) during a normal work period at an above ground iron ore mining/processing site ($Site_1$) and at an iron ore processing/shipping port ($Site_2$).

	Fatigue [a]			Mood			RPE	
	Pre	**Mid**	**Post**	**Pre**	**Mid**	**Post**	**Mid**	**Post**
$Site_1$	2.7 ± 1.7	2.8 ± 1.6	3.9 ± 1.8	7.6 ± 1.6	7.0 ± 1.9	7.1 ± 1.9	3.9 ± 1.6	4.3 ± 1.6
$Site_2$	2.0 ± 1.2	2.9 ± 1.7	3.4 ± 1.8	7.5 ± 2.3	7.1 ± 2.3	7.2 ± 2.2	4.5 ± 1.8	4.4 ± 2.0

Note: all values measured using a 10-point scale (1 to 10). [a] significant time effect; post-shift greater compared with pre- and mid-shift.

Figures

Figure 1. Mean (± SD) core temperature (bottom) for Site$_1$ (closed squares) and Site$_2$ (open squares) and individuals core temperature values for Site$_1$ (top) and Site$_2$ (middle) measured pre-, mid-, and post-shift. * Significant main effect for time > than pre-values.

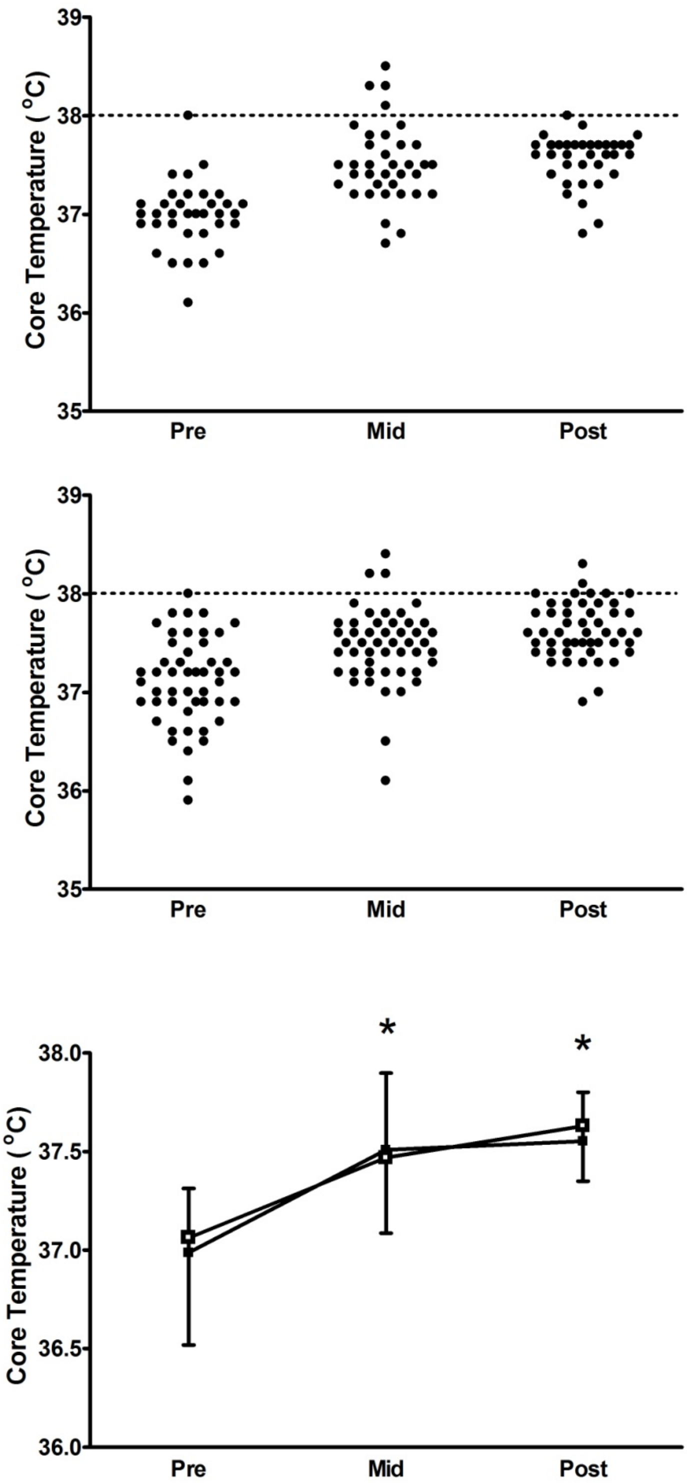

Figure 2. Mean (± SD) urine specific gravity (USG; bottom) for Site$_1$ (closed squares) and Site$_2$ (open squares) and individual USG values for Site$_1$ (top) and Site$_2$ (middle) measured pre- and post-shift. † Significant main effect for site.