Journal of Athletic Training 2017;52(11):1056–1064
doi: 10.4085/1062-6050-52.11.15

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original research

The Heat Strain of Various Athletic Surfaces: A Comparison Between Observed and Modeled Wet-Bulb Globe Temperatures

J. Luke Pryor, PhD, ATC, CSCS*†‡; Riana R. Pryor, PhD, ATC*†‡; Andrew Grundstein, PhD§; Douglas J. Casa, PhD, ATC, FNATA, FACSM‡

*Department of Kinesiology, California State University, Fresno; †Central California Sports Science Institute, California State University, Fresno; ‡Korey Stringer Institute, Department of Kinesiology, University of Connecticutt, Storrs; §Department of Geography, Climatology Research Laboratory, University of Georgia, Athens

Context: The National Athletic Trainers' Association recommends using onsite wet-bulb globe temperature (WBGT) measurement to determine whether to modify or cancel physical activity. However, not all practitioners do so and instead they may rely on the National Weather Service (NWS) to monitor weather conditions.

Objective: To compare regional NWS WBGT estimates with local athletic-surface readings and compare WBGT measurements among various local athletic surfaces.

Design: Observational study.

Setting: Athletic fields.

Main Outcome Measure(s): Measurements from 2 identical WBGT devices were averaged on 10 athletic surfaces within an NWS station reporting radius. Athletic surfaces consisted of red and black all-weather tracks (track), blue and black hard tennis courts (tennis), nylon-knit artificial green turf, green synthetic turfgrass, volleyball sand, softball clay, natural grass (grass), and a natural lake (water). Measurements (n = 143 data pairs) were taken over 18 days (May through September) between 1 PM and 4:30 PM in direct sunlight 1.2 m above ground. The starting location was counterbalanced across surfaces. The NWS weather data were entered into an algorithm to model NWS WBGT.

Results: Black tennis, black track, red track, and volleyball sand WBGT recordings were greater than NWS estimates ($P \leq .05$). When all athletic-surface measurements were combined, NWS (26.85°C ± 2.93°C) underestimated athletic-surface WBGT measurements (27.52°C ± 3.13°C; $P < .001$). The range of difference scores (–4.42°C to 6.14°C) and the absolute mean difference (1.71°C ± 1.32°C) were large. The difference between the onsite and NWS WBGT measurements resulted in misclassification of the heat-safety activity category 45% (65/143) of the time ($\chi^2_1 = 3.857$, $P = .05$). The WBGT of water was 1.4°C to 2.7°C lower than that of all other athletic surfaces ($P = .04$). We observed no other differences among athletic surfaces but noted large WBGT measurement variability among athletic playing surfaces.

Conclusions: Clinicians should use an onsite WBGT device to determine environmental conditions and the need for modification of athletic events, especially as environmental conditions worsen. Given the large WBGT variability among athletic surfaces, WBGT measurements should be obtained from each athletic surface.

Key Words: exercise, exertional heat illnesses, environment, activity modification

Key Points

- Using National Weather Service wet-bulb globe temperature (WBGT) resulted in heat-safety category misclassification across all athletic surfaces.
- The National Weather Service WBGT underestimated the local athletic-surface heat stress, especially when the surface was black or red or made of synthetic material.
- The WBGT measurements should be taken at regular intervals on each outdoor athletic playing surface to adequately capture the environmental conditions affecting physical performance and the risk of exertional heat illness.
- Onsite WBGT measurement remains a prudent choice for determining environmental conditions and the need for heat-safety physical-activity modifications or cancellations, particularly as environmental conditions worsen.

The incidence of exertional heat illnesses (EHIs) in emergency department patients[1,2] and high school athletes[3] continues to rise despite research regarding several evidence-based strategies that mitigate the EHI risk (eg, heat acclimatization, work-rest ratios, body cooling, hydration, and education). Monitoring environmental conditions is important for preventing EHI, as strong evidence[4–6] has shown that the incidences of EHI and heat exposure are strongly correlated. Most deaths due to exertional heat stroke occurred when environmental conditions were unusually high by local standards.[7]

Given the effect of meteorologic stressors on EHI risk, occupational,[8] military,[9] and sports medicine organizations, including the National Athletic Trainers' Association[10] and American College of Sports Medicine (ACSM),[11] have recommended environmental monitoring with a wet-bulb globe temperature (WBGT) device for heat-safety activity categorization and practice or event modification or cancellation. The WBGT index is calculated as a weighted average of the wet-bulb temperature (WB), dry-bulb temperature (DB), and globe temperature (GT) accordingly: $WBGT = 0.7 \times WB + 0.2 \times GT + 0.1 \times DB$.[12] Recently, Grundstein et al[13] suggested modifying the ACSM's WBGT heat-safety guidelines by adjusting threshold cutoffs to account for regional geographic variations in heat exposure and acclimatization to enhance their effectiveness.

Onsite WBGT measurements are recommended before physical activity to best approximate the true heat-exposure effects on athletes' health, safety, and performance.[8–11,14–16] However, environmental monitoring using WBGT devices is not universal practice for many reasons, including the cost of the device and the logistics of obtaining the recording (eg, time, 1 device or person but multiple athletic surfaces in use). In lieu of direct WBGT measures, practitioners may use estimates computed from standard weather-station measurements,[17,18] such as those provided by the National Weather Service (NWS) automated surface observing systems (ASOSs) or state environmental monitoring mesonets (eg, Delaware Environmental Observing System, University of Georgia Weather Network, Oklahoma Mesonet), to determine the need for practice or event modification or cancellation. A *mesonet* is a network of regional weather stations located in close proximity for observing meteorologic phenomena. Authors of several studies[16,19,20] have examined the feasibility of using modeled WBGTs but have compared these values with WBGT measurements taken adjacent to the meteorologic observing station. Therefore, the physical environmental conditions, including surface type and any sheltering, would be identical. However, to our knowledge, no one has investigated how modeled WBGTs from weather-station data vary among the different surfaces and environments commonly used in athletics. Variations in surface type ranging from hard tennis courts to artificial turf to natural grass, along with trees, stadiums, and buildings surrounding athletic surfaces, may affect wind, relative humidity, and radiation, creating local microenvironment variability in WBGT measurements compared with standardized conditions at weather stations.[15,21,22] As such, each unique microenvironment may not be accurately represented by the meteorologic conditions present at weather-observing stations; these stations are typically located on a natural surface, such as grass, and often in open areas, such as airports, resulting in misclassification of activity-modification guidelines.[15]

Determining whether environmental conditions differ among athletic surfaces and whether modeled WBGTs provide an acceptable surrogate for onsite measurements across modern athletic surfaces has safety and logistical implications for clinicians and medical staff covering multiple sports on several athletic surfaces at one time. Therefore, the first purpose of this study was to compare modeled WBGTs using data from the nearest NWS ASOS with onsite measurements from various local athletic surfaces. Our second purpose was to evaluate local WBGT measurement congruence among modern athletic surfaces with various physical properties.

METHODS

We conducted an observational study to evaluate the concordance of meteorologic data among athletic surfaces with varying physical properties and how these athletic surface data agreed with meteorologic data from the closest regional NWS ASOS. The athletic surfaces in this study represent modern athletic surfaces for the most common collegiate and high school sports. Athletic surfaces consisted of red and black all-weather tracks (track), blue and black hard tennis courts (tennis), nylon-knit artificial green turf (AstroTurf; SportGroup, Burgheim, Germany), green synthetic turfgrass with black rubber pellets (synthetic turfgrass), volleyball sand, softball clay, natural grass (grass), and a natural lake (water). The blue tennis court was a colored concrete mix, and the black tennis court was an asphalt construction. The starting location for data collection was counterbalanced among data-collection days across surfaces to control for the influence of time of day and duration of solar radiation on athletic surfaces.

Meteorologic measurements were taken over 18 days from 2012 to 2014 in the northeastern United States from May through September when solar zenith angles were equal to or less than 45°. Data were collected between 1 PM and 4:30 PM to approximate outdoor practice and competition times and in direct sunlight on days when the NWS-reported air temperature was 22.5°C to 35.6°C. Each day, data were obtained at the same location on each athletic playing surface. Measurements were not taken if the surface was being repaired at the time of measurement ($n = 2$), if the WBGT device malfunctioned ($n = 4$), or in inclement weather ($n = 10$), resulting in a total of 143 data pairs (local and NWS data points).

Preliminary Experiment

Initial measurements were collected 0.61 m above the ground to determine if playing surface proximity affected meteorologic measures due to radiative heat gain from the surface and 1.2 m above the ground to approximate the environmental stress experienced by athletes at chest level.[23] Preliminary analysis of WBGT values between heights (0.61 versus 1.2 m) revealed no differences ($P > .05$) and a strong intraclass correlation coefficient (ICC; 2,1) among surfaces (ICC [2,1] $\geq$ 0.92). Therefore, only data from 1.2 m were subsequently analyzed because this height approximates the environmental stress experienced at the torso,[23] with the exception of water, which was measured 0.61 m above the water surface to mimic the environmental stress of crew athletes.

The WBGT Device

We collected onsite meteorologic data using 2 WBGT devices (Kestrel 4600 Heat Stress Tracker; Nielsen-Kellerman, Boothwyn, PA) and reported the averages. Kestrel WBGT devices measure DB directly using an externally mounted, hermetically sealed thermistor. The GT is estimated using a hermetically sealed 25.4-mm black-globe temperature corrected to a standard 150-mm black globe, air velocity, DB, and emissivity.[24] We estimated natural WB from shaded DB and calculated pressure by the piezoresistive effect, relative humidity by electronic capacitance, and air velocity by vane anemometer accord-

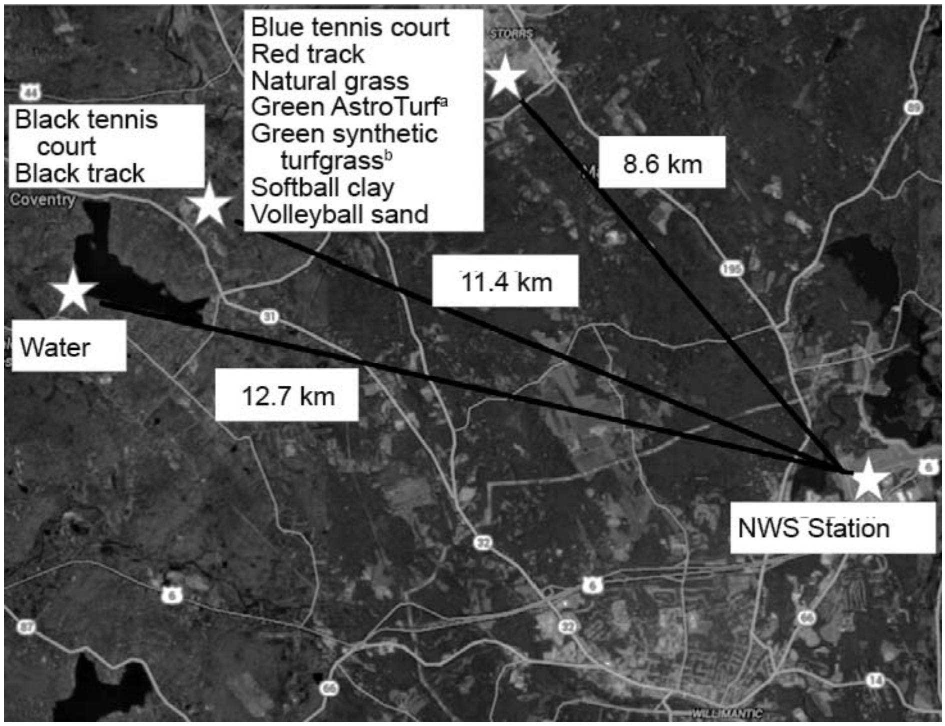

Figure 1. Locations of athletic surfaces in relation to the regional National Weather Service (NWS) station. [a] AstroTurf; SportGroup, Burgheim, Germany. [b] Green synthetic turfgrass with black rubber pellets.

ing to Bernard and Pourmoghani.[25] Manufacturer-reported accuracy is as follows: wind speed ±3%, air temperature ±0.5°C, GT ±1.4°C, relative humidity ±2%, WB ±0.8°C, and WBGT ±1.8°C.

The WBGT devices were calibrated according to the manufacturer's instructions, and data were recorded after meteorologic values stabilized (at least 7 minutes). High reliability among devices was observed for air temperature (ICC [2,1] = 0.97), relative humidity (ICC [2,1] = 0.96), WB (ICC [2,1] = 0.96), GT (ICC [2,1] = 0.91), DB (ICC [2,1] = 0.99), and WBGT (ICC [2,1] = 0.99). Accounting for travel between athletic surfaces and WBGT-device recalibration on each athletic surface, the average interval between measures was 17.8 ± 3.4 minutes.

Modeled WBGT

The WBGT was modeled using the algorithm of Liljegren et al,[16] which has repeatedly been shown to provide the most valid assessment of outdoor WBGT.[17,19] The model requires a variety of meteorologic input variables. Air temperature, relative humidity, and wind speed were obtained from the NWS ASOS located at the Willimantic-Windham Airport in Windham, Connecticut (41.74°N, 72.18°W). This station ranged from 8.6 to 12.7 km away from the athletic surfaces (Figure 1). The observing station used a standardized setup and equipment to record meteorologic measurements, with thermometer and hygrometer readings taken 1.5 m above a grass-covered surface. Wind speeds were measured at a height of 10 m and were mathematically corrected to 2 m to approximate onsite measurement height. Finally, hourly solar radiation values were obtained from the National Solar Radiation Database.[26] The WBGT was modeled at an hourly resolution to match that of the solar-radiation data. Observed WBGT was matched to the nearest modeled hourly WBGT, with an average difference of 15 ± 8 minutes between observed and modeled WBGTs. Throughout this article, the modeled WBGT will be referred to as *NWS WBGT*.

The modified WBGT heat-safety category cutoffs created by Grundstein et al[13] were used to classify heat-safety thresholds. These cutoffs, based on the Georgia High School Association guidelines, are thought to conservatively adjust for regional climate differences and subsequent heat acclimatization. These adjusted heat-safety category cutoffs, therefore, represent a more robust reflection of traditional heat-safety guidelines.

Statistical Analyses

Mean differences among the various athletic playing surfaces were initially calculated. We used a priori dependent-samples t tests to evaluate WBGT differences among the various athletic playing surfaces when the mean difference was equal to or greater than 0.5°C WBGT. Bland-Altman plots were used to assess WBGT agreement between local and NWS WBGT measurements among the various athletic surfaces. A χ^2 analysis was used to determine agreement of activity guidelines among local and NWS WBGT measurements. To characterize the magnitude of difference between WBGT measures, we calculated mean differences (athletic surface − NWS). Absolute mean difference (all athletic surfaces − NWS) was calculated to determine differences regardless of direction (overestimation or underestimation). Data are expressed as means ± standard deviations, percentages, mean differences, or ranges. We analyzed the data using SPSS (version 21; IBM Corp, Armonk, NY). The α level was set at .05.

RESULTS

The onsite WBGT recordings were greater than the NWS readings for black tennis (28.48°C ± 3.11°C versus 26.80°C ± 2.60°C, respectively; $P = .001$), black track (27.74°C ± 3.23°C versus 26.63°C ± 2.68°C, respectively; $P = .041$), red track (27.81°C ± 3.12°C versus 26.74°C ± 3.11°C, respectively; $P = .02$), and volleyball sand (28.13°C ± 2.77°C versus 27.14°C ± 3.01°C, respectively; $P = .05$) surfaces. In contrast, water WBGT measurements (25.89°C ± 3.03°C) were lower than the NWS measurements (26.91°C ± 2.81°C; $P = .004$). No other difference between athletic surface and NWS WBGT was observed. The distance between each athletic surface and the weather station did not appear to affect WBGT agreement, as differences were observed at 8.4 and 11.4 km but not at 12.7 km. Across all athletic playing surfaces, NWS underestimated athletic surface WBGT measurements (26.85°C ± 2.93°C versus 27.52°C ± 3.13°C, respectively; mean difference = 0.67°C ± 2.02°C; $P < .001$). As expected, the absolute mean difference between the NWS and onsite WBGT was high (1.71°C ± 1.32°C). The range of difference scores was wide (–4.42°C to 6.14°C).

We observed no WBGT differences between similar colors or types of athletic surfaces (black versus blue tennis, red versus black track, and grass versus synthetic turfgrass or AstroTurf; Table 1). The WBGT measurements for water were consistently lower than those for all other athletic surfaces by 1.40°C to 2.70°C WBGT ($P = .04$). This difference in WBGT can be explained by lower GT for water (37.16°C ± 3.92°C) than for the aggregate of all other surfaces (42.06°C ± 3.98°C; $P < .001$). The large WBGT measurement variability among athletic playing surfaces is shown in Table 1.

Across all athletic playing surfaces, the WBGT differences between the NWS and onsite measurements were explained by higher onsite WB (22.28°C ± 2.79°C versus 23.84°C ± 3.16°C, respectively; $P < .01$) and DB (28.83°C ± 3.43°C versus 30.29°C ± 3.21°C, respectively; $P < .01$). Wind speed (1.03 ± 1.22 m/s versus 0.95 ± 1.78 m/s, respectively; $P = .11$) and GT (41.83°C ± 4.79°C versus 41.59°C ± 4.19°C, respectively; $P = .59$) were not different between the NWS and onsite measurements. The NWS wind speeds were less variable than onsite wind speeds (ranges = 0.5–2.3 m/s versus 0.0–4.2 m/s, respectively). The relative humidity measurement was greater at the NWS stations than on the local surfaces (44.55% ± 6.99% versus 42.64% ± 8.55%, respectively; $P < .001$).

Bland-Altman analysis showed that the mean bias of NWS WBGT was less than that of the onsite WBGT measures for all athletic surfaces except for the red track and water (Figure 2). Almost all (136/144) NWS WBGT measurements were within the limits of agreement for onsite WBGT measures throughout our measurement range (19.60°C–33.65°C). In contrast, the difference between onsite and NWS WBGT measurements resulted in misclassification of the heat-safety activity category 45% (65/143) of the time ($\chi^2_1 = 3.857$, $P = .05$). The NWS underestimated heat-safety activity by 1 category 31% (44/143), by 2 categories 5% (7/143), and by 3 categories less than 1% (1/143) of the time. The NWS WBGT measurements rarely overestimated athletic-surface WBGT heat-safety activity categories, missing by 1 category 9% (13/143) of the time. We qualitatively evaluated whether category misclassification depended on athletic surface type. The NWS readings misclassified heat-safety category 33% to 60% of the time across all surfaces, with errors occurring most often on AstroTurf (60%; 9/15), red track (53%; 8/15), grass (53%; 8/15), and black tennis (50%; 7/14). As WBGT increased, agreement regarding heat-safety activity guidelines decreased between the NWS and onsite WBGT measurements (Table 2). This indicated that practitioners should assess local WBGT measurements instead of relying on data from the NWS to ensure appropriate activity-guideline categories at their specific locations. Misclassification of the heat-safety activity-guideline category between local and NWS WBGTs is illustrated in Figure 3 by data pairs that do not lie inside the shaded gray areas on the grid.

DISCUSSION

The first purpose of our study was to compare the NWS WBGT estimates with local athletic-surface WBGT measurements within the NWS reporting range and to assess how location (NWS versus onsite) affected WBGT heat-safety–category classification. We used 2 automated WBGT devices to record onsite measurements across 10 athletic surfaces and created a model NWS WBGT using an optimized algorithm for comparison.[16,19]

Our main finding was that NWS WBGT underestimated the onsite WBGT measurements by 0.67°C. Coyle[18] (0.5°C ± 2.0°C) and Cheuvront et al[15] (1.9°C ± 2.4°C) demonstrated underestimation of WBGT values when comparing regional NWS data and local athletic-surface recordings. The large difference observed by Cheuvront et al[15] was likely due to the type and color of the surface where temperatures were recorded. They compared black asphalt with grass (NWS), whereas we compared grass (NWS) with 8 surface types and 5 surface-type colors. Our data supported these findings, as WBGT measurements on black athletic surfaces ranged from 1.11°C to 1.68°C greater than the NWS estimates. Given that the modeled WBGT data were collected over grass, it is logical that the model would perform better against natural surfaces. Researchers[15,16,19,27,28] have also observed greater differences in WBGT measurements between natural and synthetic surfaces than between 2 natural surfaces. Whereas WBGT measurements between the NWS and grass were similar in our study, misclassification of the heat-safety category using the NWS value remained high (53%), suggesting that onsite WBGT measurement remains a prudent choice. In summary, it appears that the WBGT derived from NWS data underestimates local athletic-surface heat stress, particularly if the surface color is black or red or the surface is made of synthetic material.

The practical implication of these WBGT differences is the large heat-safety category misclassification by the NWS. We are the first to evaluate the agreement of WBGT heat-safety category classification among NWS and onsite measurements across several athletic surface types and colors. We observed that, when using modeled NWS WBGT data, category misclassification occurred frequently

Table 1. **Wet-Bulb Globe Temperature (°C) Difference Scores ± SDs (Ranges) Among Various Athletic Surfaces[a,b]**

Surface	Natural Grass	Softball Clay	Volleyball Sand	Green Synthetic Turfgrass[c]	Green AstroTurf[d]	Blue Tennis Court	Black Tennis Court	Red Track	Black Track	Water
Natural grass										
Softball clay	0.72 ± 1.60 (−2.45 to 4.10)									
Volleyball sand	−0.19 ± 2.11 (−3.42 to 3.45)	−0.89 ± 1.27 (−2.65 to 1.90)[e]								
Green synthetic turfgrass[c]	0.09 ± 2.33 (−3.50 to 4.05)	−0.63 ± 1.53 (−3.75 to 1.05)	0.26 ± 1.19 (−1.50 to 2.65)							
Green AstroTurf[d]	0.61 ± 1.88 (−2.25 to 3.45)	0.54 ± 2.26 (−3.65 to 5.20)	0.78 ± 2.10 (−3.15 to 4.45)	0.52 ± 2.27 (−3.65 to 5.20)						
Blue tennis court	0.30 ± 1.94 (−3.85 to 3.95)	−0.13 ± 1.31 (−4.10 to 0.95)	0.78 ± 1.65 (−1.85 to 3.50)	0.37 ± 1.28 (−1.80 to 3.10)	−0.07 ± 1.86 (−3.60 to 1.86)					
Black tennis court	−0.57 ± 1.80 (−4.65 to 2.20)	−1.29 ± 0.99 (−3.00 to 0.65)[e]	−0.40 ± 1.34 (−2.30 to 2.40)	−0.67 ± 1.59 (−2.55 to 3.35)	−1.18 ± 1.53 (−4.30 to 1.10)[e]	−1.11 ± 1.89 (−3.85 to 3.70)				
Red track	0.30 ± 1.86 (−3.00 to 4.25)	−0.51 ± 0.95 (−2.40 to 1.15)[e]	0.47 ± 1.74 (−2.95 to 3.20)	0.20 ± 1.91 (−3.45 to 2.95)	−0.40 ± 0.97 (−2.35 to 1.30)	−0.34 ± 1.45 (−1.90 to 3.30)	0.87 ± 1.35 (−0.90 to 3.55)			
Black track	0.11 ± 2.07 (−4.60 to 3.10)	−0.61 ± 1.14 (−3.00 to 1.20)	0.28 ± 1.70 (−3.00 to 3.55)	0.02 ± 1.90 (−2.10 to 4.45)	−0.50 ± 1.19 (−2.65 to 1.80)	−0.45 ± 1.82 (−3.85 to 3.15)	0.68 ± 1.10 (−0.70 to 3.55)[e]	−0.19 ± 1.36 (−3.55 to 1.60)		
Water	2.12 ± 1.83 (−1.25 to 5.70)[e]	1.40 ± 1.03 (−0.45 to 3.25)[e]	2.29 ± 1.73 (−0.80 to 5.00)[e]	2.03 ± 2.08 (−1.30 to 5.95)[e]	1.51 ± 0.90 (−0.15 to 2.70)[e]	1.52 ± 1.82 (−1.30 to 6.30)[e]	2.70 ± 1.19 (0.75 to 4.90)[e]	1.83 ± 0.68 (0.60 to 3.00)[e]	2.02 ± 1.41 (0.45 to 4.90)[e]	

[a] Mean difference calculated as horizontal surface column – vertical surface column.
[b] Negative values indicate that the vertical surface column was hotter, whereas positive values indicate that the horizontal surface column was hotter.
[c] Synthetic turfgrass with black rubber pellets.
[d] AstroTurf; SportGroup, Burgheim, Germany.
[e] $P < .05$.

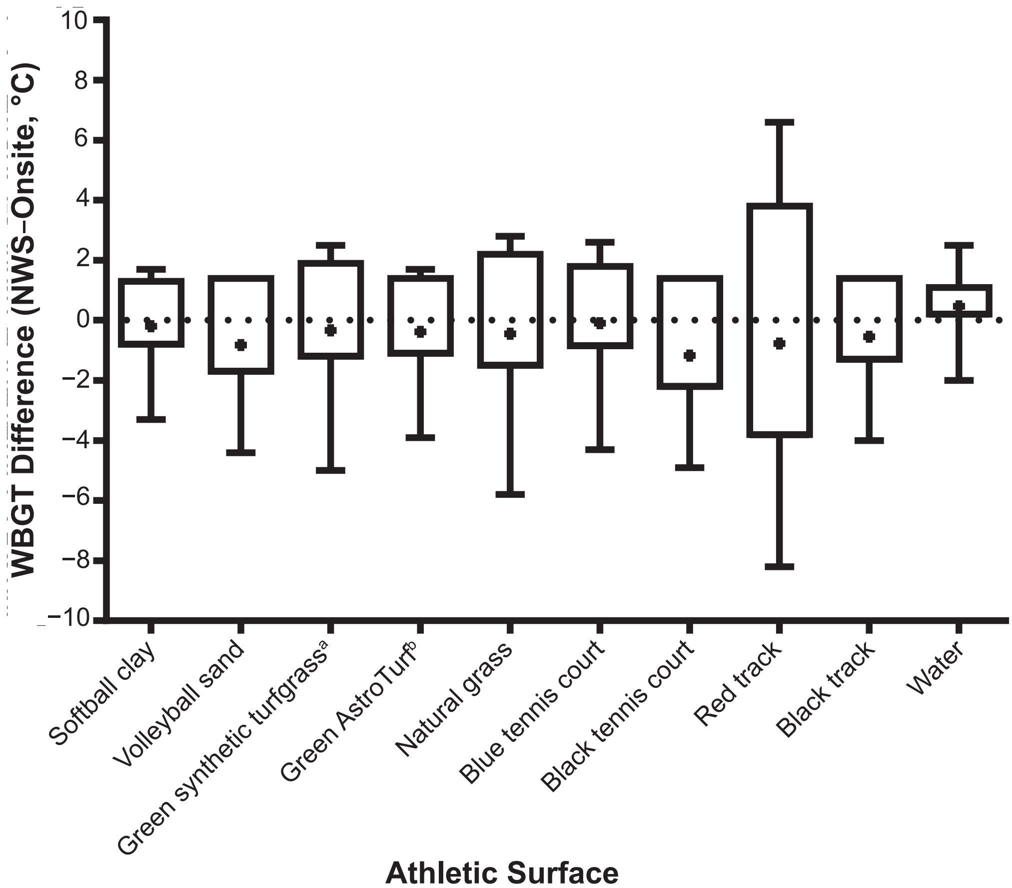

Figure 2. Mean bias, standard deviation, and 95% limits of agreement from Bland-Altman graphs. Solid dot represents mean bias (National Weather Service [NWS] – onsite wet-bulb globe temperature [WBGT]). Box ends indicate standard deviation bias, and whiskers represent 95% limits of agreement. [a] Green synthetic turfgrass with black rubber pellets. [b] AstroTurf; SportGroup, Burgheim, Germany.

(≥50%) on AstroTurf, red track, grass, and black tennis surfaces. In fact, category misclassification occurred across all athletic surfaces, albeit less often (33% to 44%). When all athletic surfaces were combined, the modeled NWS WBGT incorrectly identified the heat-safety category classification for 45% of the paired measurements. The modeled NWS WBGT underestimated the onsite WBGT by 1 category recurrently (31%), but we also observed mismatches by 2 (5%) and 3 (1%) categories (Figure 3). This finding mirrored the work of Cheuvront et al,[15] who also showed dissonance of heat-safety category classification when using NWS data to model onsite WBGT.

In addition, we evaluated the congruence between NWS and onsite WBGT heat-safety categories as WBGT increased within our dataset. The heat-safety–category agreement of the NWS WBGT with the onsite WBGT decreased as ambient conditions became progressively oppressive (Table 1). This alarming trend could create an extremely unsafe situation. If NWS data are used, athletic trainers may not prudently implement proper physical activity modifications when environmental conditions warrant, resulting in a dangerous increase in the risk of EHI. Heat-safety activity guidelines use evidence-based strategies designed to mitigate internal and external heat production by providing frequent rest and hydration breaks, reducing activity duration and intensity, minimizing or removing equipment, and moving practice earlier or later in the day when weather conditions are typically milder.[10,13,29] In this way, the EHI risk is reduced.

The second purpose of our study was to compare WBGT measurements among the various athletic surfaces to determine whether WBGT recordings on athletic surfaces in close proximity are needed. We observed that WBGT measurements among athletic surfaces were not different except for water, which was consistently lower than for all other surfaces (Table 2). Albeit not statistically significant, the mean differences among the various athletic surfaces were large, ranging from –1.29°C to 0.87°C. This large range of mean differences suggests that WBGT measurements should be taken on each athletic playing surface at regular intervals to adequately capture the true environmental conditions that affect physical performance and the risk of EHI. Such variable contrasts among surfaces were likely caused by the shelter effect, whereby surrounding natural and artificial structures affect meteorologic measures that factor into the WBGT calculation (humidity, wind speed, and solar radiation), creating unique microenvironments. Kopec[27] evaluated athletic-surface WBGT congruence by comparing green AstroTurf, tennis courts (hard and soft), and an asphalt parking lot with grass. The deviation between grass and the athletic surfaces ranged from 0.16°C to 0.72°C, somewhat comparable with our data in which similar surfaces were compared (–0.57°C to 0.61°C). In all, our study provides empirical evidence

Table 2. **Regional Heat-Safety Activity Guidelines,[a] Percentage of Measures in Each Category Classification, and National Weather Service Category Agreement With Onsite Devices Reported as Percentages[b]**

Wet-Bulb Globe Temperature, °C	Activity Guidelines	Wet-Bulb Globe Temperature, % (n/N)		National Weather Service Correct, % (n/N)[c]
		Onsite	National Weather Service	
<26.5	Normal activities: provide at least 3 separate rest breaks each hour with a minimum duration of 3 min each during the workout.	37.8 (54/143)	46.2 (66/143)	100 (54/54)
26.6–29.2	Use discretion for intense or prolonged exercise; watch at-risk players carefully. Provide at least 3 separate rest breaks each hour with a minimum duration of 4 min each.	32.9 (47/143)	32.9 (47/143)	74.5 (35/47)
29.3–30.9	Maximum practice time is 2 h. For football, players are restricted to helmet, shoulder pads, and shorts during practice. If the wet-bulb globe temperature rises to this level during practice, players may continue to work out wearing football pants without changing to shorts. For all sports, provide at least 4 separate rest breaks each hour with a minimum duration of 4 min each.	11.9 (17/143)	11.2 (16/143)	17.6 (3/17)
31.0–32.0	Maximum practice time is 1 h. For football, no protective equipment may be worn during practice, and there may be no conditioning activities. For all sports, there must be 20 min of rest breaks distributed throughout the hour of practice.	7.7 (11/143)	5.6 (8/143)	0.0 (0/11)
≥32.1	No outdoor workouts. Delay practice until a cooler wet-bulb globe temperature level is reached.	9.8 (14/143)	4.2 (6/143)	42.9 (6/14)

[a] Examples of heat-activity modifications and regional categorization (category 2) of wet-bulb globe temperature cutoffs from Grundstein et al.[13]

[b] Adapted from *Applied Geography*, volume 56, Grundstein A, Williams C, Phan M, Cooper E, Regional heat safety thresholds for athletics in the contiguous United States, pages 55–60, 2015, with permission from Elsevier. http://www.sciencedirect.com/science/journal/01436228?sdc=1.

[c] Calculated as (number of measurements that National Weather Service correctly matched with onsite wet-bulb globe temperature category/number of onsite measurements in a category) × 100.

supporting the WBGT measurement guidelines proposed in the National Athletic Trainers' Association[10] and ACSM[11] position statements on EHI prevention and highlights the importance of onsite meteorologic assessment before and at frequent intervals when determining the need for activity modification or cancellation.

A limitation of our study was the use of only 1 NWS station to estimate WBGT. Whereas the equation of Liljegren et al[16] for outdoor WBGT modeling is most accurate,[17,19] triangulating WBGT estimates with more than 1 surrounding weather station might have enhanced the algorithm's accuracy and should be considered for future investigations. Model performance would likely also improve when weather stations (and solar-radiation data) are in close proximity to athletic sites. Many states, such as Delaware, Georgia, and Oklahoma, have high-density weather station networks (mesonets), enabling enhanced model performance. We used the modified WBGT heat-safety category cutoffs created by Grundstein et al,[13] which are thought to conservatively adjust for regional climate differences. In doing so, our category delineations were not uniform and in some cases were small (1.0°C–2.6°C), particularly as WBGT increased, which may help explain our finding that more category misclassifications were observed at higher WBGTs. Using larger WBGT heat-safety–category spans as employed by the ACSM for distance running (≥6°C)[30] and general physical activity (2.1°C)[11] or the military (1.1°C–1.7°C)[9] would have resulted in fewer misclassifications. Practically, cautiously preparing (eg, hydration, cooling stations) for extreme weather conditions and implementing additional heat-safety protocols (eg, less equipment, rest breaks) when possible is encouraged regardless of heat-safety guidelines. Finally, data were collected in southern New England, and, whereas the data are convincing, the results may be not applicable to geographic regions in the United States with extreme dry heat, such as the Southwest, or humid heat, such as the Southeast.

Practical Application

The NWS WBGT underestimated athletic-surface WBGT measurements, resulting in a large misclassification of heat-safety category, especially for red and black artificial surfaces. The agreement for heat-safety category between the local WBGT and NWS measurements decreased as WBGT increased. These findings highlight the need for practitioners to assess environmental conditions before and at regular intervals during outdoor physical activity using an onsite WBGT device. In doing so, heat-safety activity guidelines can be implemented judiciously to increase athlete safety. The wide range of WBGT measurements among athletic surfaces indicated that WBGT should be measured on each surface to determine the need for physical activity modification or cancellation. Whereas products are commercially available to calculate WBGT from NWS data, our data and those of Cheuvront et al[15] strongly suggest that onsite WBGT measurements are needed to accurately assess environmental conditions and determine the need for activity modifications.

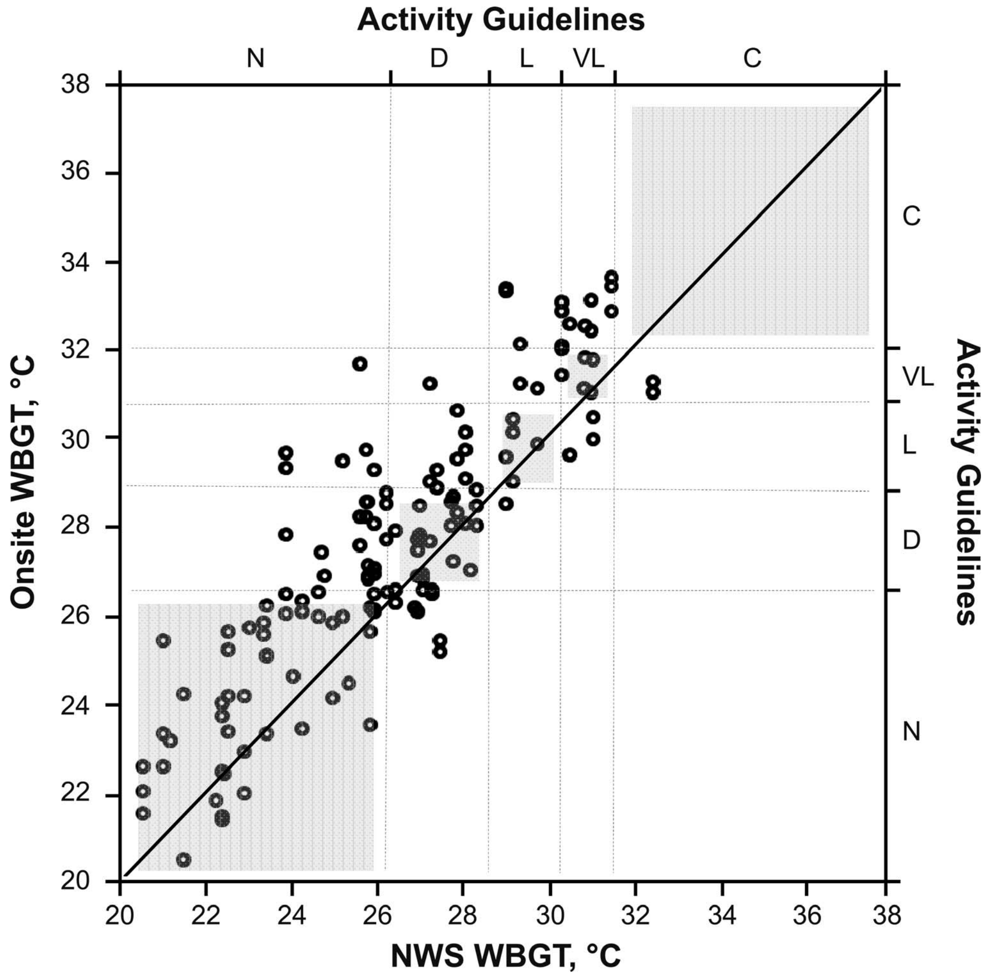

Figure 3. All local athletic surface wet-bulb globe temperatures (WBGTs) versus National Weather Service (NWS) WBGTs (N = 143 data pairs). Data points falling within shaded blocks represent agreement between measures based on category 2 regional heat safety guidelines developed by Grundstein et al.[13] Abbreviations: C, cancel outdoor workouts or delay until cooler WBGT is reached (WBGT ≥ 32.1°C); D, use discretion for intensity of prolonged exercise (WBGT range = 26.6°C –29.2°C); L, limit practice time (WBGT range = 29.3°C–30.9°C); N, normal activities (WBGT < 26.5°C); VL, very limited practice time (WBGT range = 31.0°C–32.0°C).

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Address correspondence to J. Luke Pryor, PhD, ATC, CSCS, Department of Kinesiology, California State University, Fresno, 5275 North Campus Drive, M/S SG25, Fresno, CA 93740. Address e-mail to lukepryor@csufresno.edu.