Relationship Between Running Biomechanics and Core Temperature Across a Competitive Road Race

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Background: Outdoor races introduce environmental stressors to runners, and core temperature changes may influence runners' movement patterns. This study assessed changes and determined relationships between sensor-derived running biomechanics and core temperature among runners across an 11.27-km road race.

Hypothesis: Core temperatures would increase significantly across the race, related to changes in spatiotemporal biomechanical measures.

Study Design: Cross-sectional cohort study.

Level of Evidence: Level 3.

Methods: Twenty runners (9 female, 11 male; age, 48 ± 12 years; height, 169.7 ± 9.1 cm; mass, 71.3 ± 13.4 kg) enrolled in the 2022 Falmouth Road Race were recruited. Participants used lightweight technologies (ingestible thermistors and wearable sensors) to monitor core temperature and running biomechanics throughout the race. Timestamps were used to align sensor-derived measures for 7 race segments. Observations were labeled as core temperatures generally within normal limits (<38°C) or at elevated core temperatures (≥38°C). Multivariate repeated measures analyses of variance were used to assess changes in sensor-derived measures across the race, with Bonferroni post hoc comparisons for significant findings. Pearson's r correlations were used to assess the relationship between running biomechanics and core temperature measures.

Results: Eighteen participants developed hyperthermic core temperatures (39.0°C ± 0.5°C); core temperatures increased significantly across the race ($P < 0.01$). Kinetic measures obtained from the accelerometers, including shock, impact, and braking g, all significantly increased across the race ($P < 0.01$); other sensor-derived biomechanical measures did not change significantly. Core temperatures were weakly associated with biomechanics ($|r \text{ range}|$, 0.02-0.16).

Conclusion: Core temperatures and kinetics increased significantly across a race, yet these outcomes were not strongly correlated. The observed kinetic changes may have been attributed to fatigue-related influences over the race.

Clinical Relevance: Clinicians may not expect changes in biomechanical movement patterns to signal thermal responses during outdoor running in a singular event.

Keywords: ingestible thermistor; environmental stress; weather; performance; loading

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Road races are popular competitive events in the United States, and distances ranging from 5- to 10-km attracted about 10.5 million runners in 2019 (~60% of all road race registrants).[24] There are multiple external demands that runners encounter during outdoor racing that may lead to biomechanical gait changes, including, but not limited to, changes in inclination,[22] terrain,[25] and environment.[1,2] External stressors are difficult to effectively recreate in laboratory settings,[26] and, as such, researchers have begun to incorporate validated (intraclass correlation [ICC] range, 0.57-0.94) wearable technology during outdoor running to measure spatiotemporal, kinetic, and kinematic running biomechanics.[2,4,11,12,20,23] Previous research has specifically explored the effects of inclination,[11] instantaneous speed changes,[18] running surfaces,[18] and racing environments on running biomechanics using these wearable sensors,[11] with demonstrative changes in lower extremity biomechanics compared with simulated laboratory conditions. However, there is very limited research on biomechanical gait adaptations attributed to environmental stressors and subsequent thermal responses.[1,2]

The relationship between heat stress and biomechanics during running events is important to assess given that even mild forms of exertional heat illness threaten optimal central nervous system functioning, and subsequent muscular coordination and control.[27] Neuromuscular control is requisite to completing high-level physical tests, especially during coordinated activities such as running. Thus, heat stress may affect biomechanical movement patterns during racing under environmental stress. Previous research among military personnel found that vertical and horizontal trunk accelerometry patterns became more irregular when subjects presented with life-threatening exertional heat illness and elevated core temperatures.[5] It is plausible that more running-specific biomechanical measures would respond proportionally to a range of thermal responses in a high-heat environment, although these relationships have yet to be explored.

We previously conducted a case study on a runner who completed a half-marathon race while wearing running-specific sensors, and identified spatiotemporal changes towards the end of the race.[11] The runner decreased step length markedly in the last 2 quarters of the race, accompanied with increased foot contact time.[11] Based on the runners' self-reported training log, these changes may have been attributed to heat-related fatigue as they reported the effects of the environment on their affect during the race; the ambient temperature during the race was 31°C with 81% relative humidity, or approximately 100 on the Heat Index.[13,14] Such biomechanical alterations as observed during extreme weather conditions have been linked extensively with musculoskeletal lower extremity injuries, and may pose a threat to runners' overall health and wellbeing.[13,21,28,29] Whereas these changes were observed in an isolated case, these findings speak to a larger clinical problem in that heat responses during running may influence runners' movement patterns and potentially contribute to the running-related injury burden.

We are aware of 1 study that explicitly assessed the influence of various environmental conditions (winter, spring conditions) on outdoor running biomechanics, and the researchers did not identify consistent biomechanical adaptations across runners for the various environmental changes.[1] However, the research team did not specifically assess core temperature to link the thermal response to movement variation. Conversely, several studies have estimated core body temperature through heartrate data monitoring in practical scenarios,[5,6] and coupled these assessments with trunk-worn accelerometry data to predict movement variations among cadets in extreme heat conditions.[5] However, to our knowledge, such assessments have yet to be expanded to specifically measuring core temperature along with biomechanical measures among competitive outdoor runners to determine gait variations across a range of thermal responses.

Ingestible thermistors are a reliable, valid means to continuously measure core temperature to assess thermal responses to heat stress,[17] and can be used simultaneously with running-specific wearable sensors to determine the effect of heat on running performance and movement quality. The Falmouth Road Race is a historic and competitive road race (11.27 km) that takes place every August in Falmouth, Massachusetts, and has notoriously high rates of runners experiencing heat-related illnesses (7 per 1000 runners; average ambient temperatures between ~23°C and 27°C over the last 5 years).[31] Given the prevalence of heat-related illnesses in this competitive environment, and the substantial effects of heat on runners' thermal regulation,[3,7,8] it is necessary to examine runners' biomechanical and heat responses during such an outdoor competition. By implementing lightweight, validated wearable sensors, there is an opportunity to ecologically assess the relationship between heat response on running biomechanics.

The purpose of this study was 2-fold. First, we sought to assess changes in sensor-derived core temperature across the duration of an 11.27-km outdoor road race, and changes in running biomechanics across the race and across heat response statuses (core temperature typical range of within normal limits [WNL] <38°C; elevated core temperatures ≥38°C, which is the midrange of core temperature indicative of high risk for heat exhaustion).[7] We hypothesized that core temperature would increase significantly across the duration of the race, and that there would be a significant interaction between race segment and core temperature status for spatiotemporal biomechanical measures. Second, we sought to assess the relationship between sensor-derived core temperature and running biomechanics. We hypothesized that the core body temperature and sensor-derived running biomechanics would be moderately correlated, particularly for spatiotemporal outcomes.

METHODS

Study Design and Participants

We performed a cross-sectional cohort study of adult runners registered for the 2022 Falmouth Road Race. Participants were recruited through an email flyer through the official race listserv.

Potential participants were eligible for participation if they were between 18 and 70 years of age and were free from lower extremity injuries within 6 months of study participation. Exclusion criteria included previous lower extremity or back surgery, neuromuscular or cardiovascular disorders, cold urticaria, or known pregnancy. Potential participants were also excluded if they had any contraindications to the ingestible thermometer procedures, including body weight <80 lb (~36.29 kg), gastrointestinal conditions, any planned magnetic resonance imaging procedures, or implanted devices. All participants provided written informed consent before study participation, and the protocol was approved via the primary institution's review board (Protocol No. H22-0047).

Instrumentation for Primary Outcome Measures

RunScribe Plus (Scribe Labs, Inc) wearable sensors were used to conduct racing biomechanical assessments. The sensors are lightweight (15 g, 35 mm × 25 mm × 7.5 mm) with a 500 Hz sampling rate with 32 MB of onboard processing and memory to obtain step-by-step data during sustained running. The sensors have demonstrated fair-to-excellent validity against gold standard laboratory equipment to measure spatiotemporal (ICC, 0.86-0.94), kinetic (ICC, 0.89-0.92), and kinematic (ICC, 0.57-0.74) running biomechanics.[4,12,20] Ingestible thermometers (eCelsius, BodyCAP) were used to collect all core temperature data. The thermometers are wireless, silicone-coated temperature sensing pills (17.7 mm long × 8.9 mm diameter) that transmit core temperature data sampled every 15 seconds instantaneously to a connected handheld data recorder. The ingestible thermometers have been found to be accurate within ~0.2°C of rectal thermometry readings.[17]

Procedures

All laboratory testing procedures were performed at the primary institution's laboratory. Participants reported to the research laboratory for a single visit before the race, and underwent anthropomorphic assessments to determine height, weight, and body composition (BodPod, COSMED). Participants were then assigned a set of the running wearable sensors, and a member of the research team mounted the sensors bilaterally on the laces of the shoes. Participants stood with equal weight on both feet, and then ran briefly on an indoor treadmill as means to calibrate the sensors. Following running sensor familiarization and calibration, participants then completed a standardized maximal oxygen consumption (VO_2max) test on a motorized treadmill (T150, COSMED) with open-circuit spirometry (TrueOne 2400, Parvo Medics Inc) to assess runners' fitness levels using established American College of Sports Medicine criteria. At the end of the laboratory visit, all participants were provided with an ingestible thermometer and instructions on proper usage to ensure viable data throughout the race.

Participants were instructed to swallow the ingestible thermometer 6 to 8 hours before the start of the race. Just before starting the race, a member of the research team secured the same set of running wearable sensors on participants' shoes and were calibrated to foot positioning. Both sets of sensors recorded thermal and biomechanical data throughout the duration of the race. Study personnel were present at the medical tent at the end of the race to retrieve the sensors, and ensured that runners with temperatures indicative of risk of heat-illness were directed or escorted to onsite race medical personnel.[3,7] Participation in the study was complete at the conclusion of the race.

Data Processing

Step-by-step biomechanical data from the running wearable sensors were transmitted via Bluetooth to an associated research account through the sensor company's online dashboard. The specific biomechanical variables were all calculated on board the sensors,[12,13,20] with operational definitions published elsewhere.[13] Participants' biomechanical data with timestamps for each limb were extracted from the dashboard by downloading .csv files from each foot pod for analyses. Walking and standing events were identified visually in the datasets from when the flight ratio variable fell to zero and were removed from analyses. Ingestible thermometer data were similarly transmitted and extracted for analyses. Data from the ingestible thermometer were inspected to identify erroneous datapoints beyond normal biological ranges, increasing or decreasing temperatures at improbable rates (>0.50°C/min), or that were associated with poor capsule ingestion timeframes.[10] Timestamps from both datastreams were used to synchronize the observations and split the race data into 7 segments. The data were labeled accordingly, and average biomechanical and core temperature data were calculated per race segment (1-7) for each participant. Core temperature readings were used to categorize whether participants' datapoints were generally WNL (<38°C), or at elevated core temperatures ≥38°C.[22]

Statistical Analyses

Sensor-derived biomechanical data reflected that a minimum difference in contact time of 18 ± 19 ms was needed to achieve 80% power at an alpha level of 0.05.[14] As such, we required a sample size of at least 18 runners to detect biomechanical changes over the course of the race attributed to responses to environmental stress. Descriptive statistics were used to assess demographics for male and female study participants. Q-Q plots were used to assess for normality across all biomechanical and core temperature data, which reflected that the data were distributed normally and that parametric tests were appropriate. Pearson's r correlations were used to determine whether multicollinearity ($r \geq 0.60$) existed across biomechanical variables. These preliminary assessments reflected that most spatiotemporal ($r = |0.60\text{-}0.90|$), kinetic ($r = |0.59\text{-}0.94|$), and kinematic measures ($r = 0.63$) were moderately to strongly correlated, supporting multivariate assessments for these subcategories of variables. Thus, separate multivariate repeated measures analyses of covariance (RMANCOVA; covariates: sex, speed) were used to assess changes in spatiotemporal, kinetic,

Table 1. Participant demographics

Outcome Measure	Female (N = 9) Mean ± SD	Male (N = 11) Mean ± SD	All Participants (N = 20) Mean ± SD
Age, y	48.2 ± 10.5	47.1 ± 13.7	47.6 ± 12.0
Height, cm	162.7 ± 7.1	175.3 ± 6.1	169.7 ± 9.1
Mass, kg	62.8 ± 12.7	78.2 ± 9.9	71.3 ± 13.4
Fat-free mass, kg	47.6 ± 7.6	62.9 ± 8.3	56.0 ± 10.9
Fat mass, kg	18.1 ± 11.4	15.5 ± 3.8	16.7 ± 8.0
Body fat, %	25.8 ± 11.6	19.7 ± 4.0	22.5 ± 8.6
VO_2max, mL/kg/min	42.8 ± 8.5	51.4 ± 4.2	47.5 ± 7.7

VO_2max, maximal oxygen consumption.

and kinematic measures across race segments (1-7) of the road race, and across heat statuses (WNL, elevated core temperature). Given the multiple comparisons, Bonferroni post hoc assessments were conducted for significant findings (adjusted $P < 0.01$). A RMANCOVA was also used to assess changes in core temperature across the race using the same conservative post hoc test approach. To address the secondary study aim, Pearson's r correlations were used to assess the relationship between core temperature and running biomechanics. The strength of the relationships were interpreted as ≤0.2 negligible, 0.21 to 0.49 small, 0.50 to 0.79 moderate, and ≥0.80 large.[19] All analyses were conducted in R (RStudio, Version 1.2.1335).

RESULTS

A total of 27 participants enrolled in the study; however, data from the ingestible thermometers were not viable for 7 participants based on data screening specified in the data processing methods. As such, data from 20 total participants were analyzed in this study, which met adequate study power (Table 1). A total of 18 participants fit the specified elevated core temperature threshold during the race (39.0°C ± 0.5°C; Table 2). The ambient temperature during the race ranged from 21.2 to 27.4°C, with relative humidity between 71.8% and 98.0%, and wet bulb globe temperature readings between 21.0°C and 29.7°C.

Within-participant core temperature readings were found to differ significantly across the duration of the race ($P < 0.01$). Post hoc analyses reflected that core temperatures significantly and steadily increased across the duration of the run ($P < 0.01$) (Figure 1a and Table 2).

There was a significant main effect for kinetic variables by segment across the race while accounting for sex and speed covariates ($P < 0.01$). Post hoc assessments reflected that shock ($P < 0.01$), impact g ($P < 0.01$), and braking g ($P < 0.01$) values increased significantly across the duration of the race (Figure 1b-d; Table 2). However, there was not a significant main effect for heat status ($P = 0.89$) nor an interaction between race segment and heat status ($P = 0.92$) for kinetic measures. There were no significant differences in spatiotemporal nor kinematic biomechanical variables across race segments (P range, 0.80-0.81), across heat statuses (P range, 0.36-0.50), and no interaction between race segment and heat status while accounting for sex and speed covariates (P range: 0.80-0.83). Core temperatures were trivially to weakly associated with biomechanical outcomes ($|r$ range$| = 0.02$-0.16) (Figure 2).

DISCUSSION

Overall, we identified that participants' core temperature readings increased across the duration of a 11.27-km road race under high heat conditions, which aligned with expected thermal responses and previous heat-related epidemiology from this particular event.[31] Although we also identified several changes in runners' biomechanical measures across the duration of the race, these changes were not significantly related to core temperature readings. These findings were in contrast to our primary study hypotheses. Our findings cumulatively suggest that within-session changes in core temperature may not have a substantial influence on running road race biomechanics, even in the presence of highly elevated core temperature values, meeting the midrange of core temperature criteria for risk of heat-related illness.[7]

We initially anticipated that runners would present with significant changes in sensor-derived spatiotemporal running biomechanics toward the later stages in the road race, as these changes have previously been identified with a race case study in a high heat environment.[11] We did not identify significant changes in spatiotemporal biomechanics across the race nor did we find a strong relationship between these measures and core temperature readings. These findings indicate that spatiotemporal changes may be influenced more strongly by other extrinsic factors, such as terrain, inclination, and running

Table 2. Core body temperatures and running biomechanics across the 7-mile race

Outcome Measure	Mile 1	Mile 2	Mile 3	Mile 4	Mile 5	Mile 6	Mile 7
Core body temperature, °C	37.6 ± 0.4	38.1 ± 0.4	38.5 ± 0.5	38.7 ±0.9	38.9 ± 0.8	39.1 ± 0.6	39.2 ± 0.7
Pace, m/s	3.2 ± 0.5	3.1 ± 0.5	3.1 ± 0.5	3.1 ± 0.5	3.1 ± 0.5	3.0 ± 0.5	3.1 ± 0.5
Cadence, steps/min	174 ± 11	173 ± 12	173 ± 12	173 ± 13	173 ± 12	173 ± 12	173 ± 12
Stride length, m	2.2 ± 0.3	2.2 ± 0.3	2.1 ± 0.3	2.2 ± 0.3	2.1 ± 0.3	2.1 ± 0.3	2.1 ± 0.3
Contact time, ms	295 ± 40	298 ± 45	303 ± 50	302 ± 53	304 ± 50	305 ± 48	303 ± 47
Flight ratio, %	15.4 ± 8.1	15.0 ± 8.2	14.3 ± 8.0	14.5 ± 8.0	13.7 ± 8.2	13.4 ± 8.1	13.9 ± 7.7
Shock, *g*	13.1 ± 2.9	13.3 ± 3.1	13.4 ± 2.9	13.7 ± 3.0	13.7 ± 3.0	13.8 ± 3.0	14.2 ± 2.8
Impact, *g*	10.6 ± 2.7	10.7 ± 2.9	10.8 ± 2.8	11.1 ± 2.9	10.9 ± 2.9	11.1 ± 2.9	11.4 ± 2.7
Braking, *g*	7.4 ± 1.9	7.5 ± 1.8	7.7 ± 1.8	7.7 ± 1.8	7.8 ± 1.8	7.8 ± 1.8	8.0 ± 1.8
Foot strike type, 1-16 scale	8 ± 3	8 ± 3	8 ± 3	8 ± 3	8 ± 3	8 ± 3	8 ± 3
Pronation excursion, deg	15.0 ± 3.8	15.2 ± 4.2	15.0 ± 4.1	15.4 ± 4.3	15.2 ± 4.4	15.1 ± 4.2	14.9 ± 4.3
Maximum pronation velocity, deg/s	664 ± 185	674 ± 207	686 ± 213	689 ± 218	684 ± 214	683 ± 216	706 ± 213

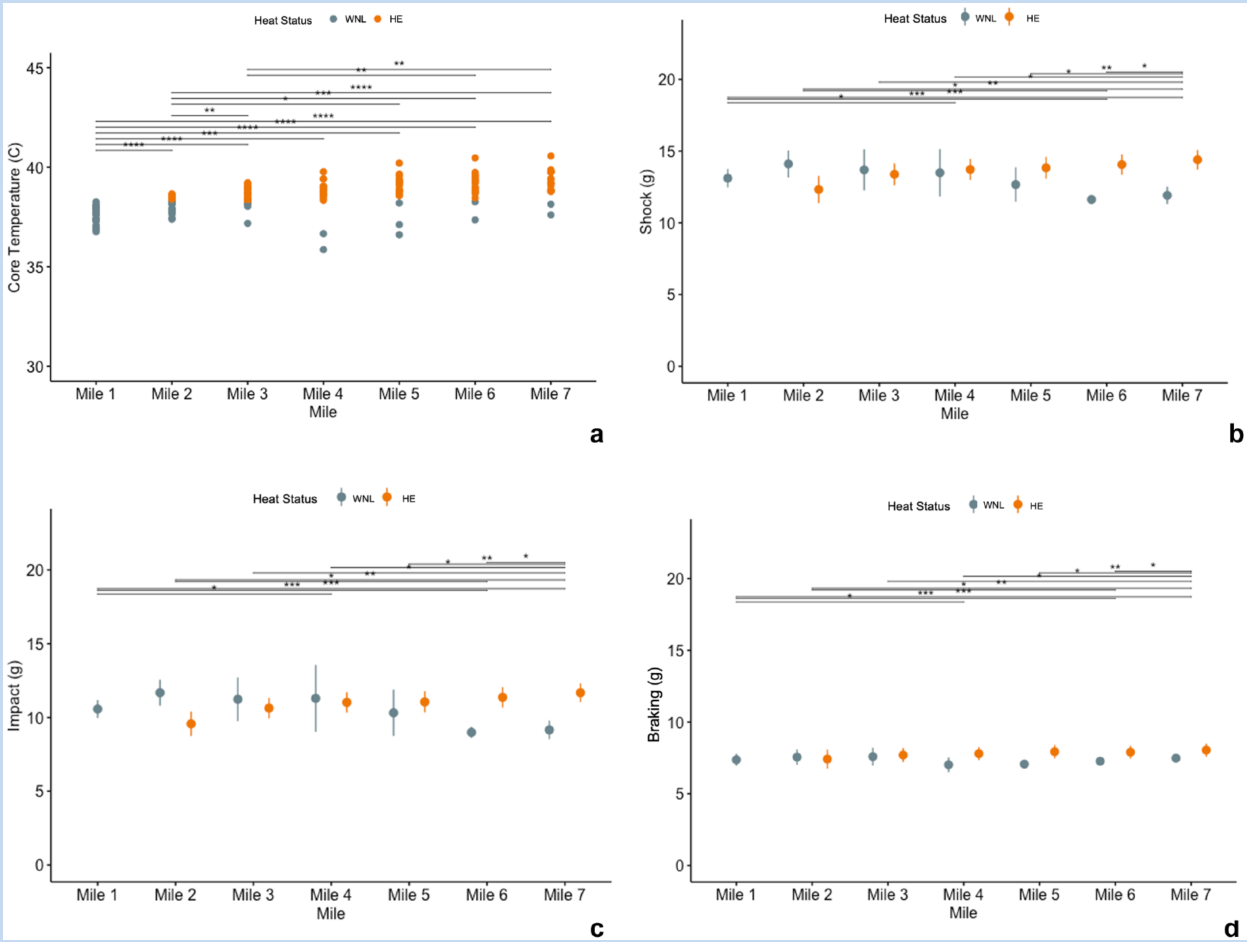

Figure 1. Heat status during 7 mile (11.27 km) race: (a) core temperature; (b) shock; (c) impact; (d) braking. HE, heat exhaustion; WNL, within normal limits.

surface as demonstrated in other investigations.[18,22,25] The race course in this study was relatively flat (total elevation gain, 184 feet) and maintains the same running surface throughout the 11.27-km duration, eliminating other potential influences on running biomechanics to narrow the focus on environmental stress.[18] Thus, our findings suggest that core temperature responses to heat stress during racing environments do not substantially influence biomechanical patterns within a single assessment timeframe. In addition, compared with the previous case study,[11] the Falmouth Road Race is considerably shorter (7 miles vs 13.1 miles), which likely contributed to the differences in findings. Future studies should explore the effects of race distance on thermal and biomechanical responses during running.

We are aware of 1 other study in which the investigators explored a range of ambient temperatures on runners' biomechanics.[1] Specifically, the authors identified more pronounced biomechanical running changes when comparing cold weather climates with warmer weather activities (ie, increased cadence during cold weather running versus warm weather running), suggesting that athletes may respond differently across a wider range of environmental conditions imposing a thermal body response.[1] However, taken together with our findings, spatiotemporal parameters do not appear to be influenced by thermal responses to heat stress within a single assessment timeframe at core temperature readings placing runners at risk of heat illness, specifically heat exhaustion. Thus, it may be warranted to consider the testing environment on expected biomechanical features during longer-term investigations, but not as pertinent for changes within a session for those that do not exhibit other signs or symptoms of heat illness. Other research that estimated core temperature readings from heartrate data among military cadets who developed heat stroke found more overt gait changes with gait variability, and thus expected changes within sessions may be more pronounced in the event of extreme thermal distress.[5] We had only 1 participant who reached core temperature values indicative of possible heat stroke (>40°C); more extreme heat responses in relationship to biomechanical measures during racing events has yet to be explored.

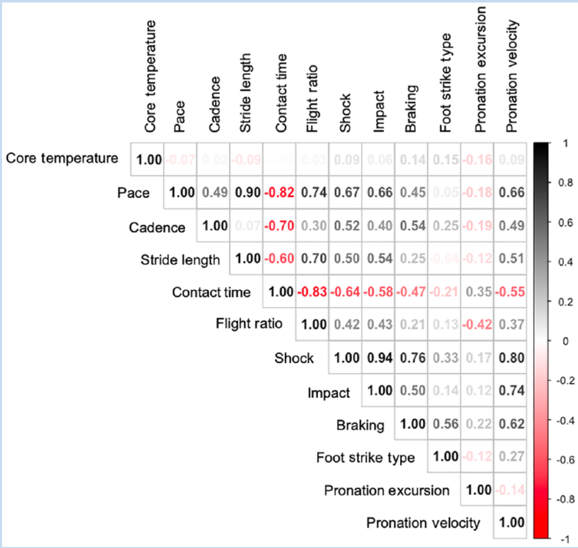

Figure 2. Association of core temperature with biomechanical outcomes. Scale: black, positive association; red, negative association.

We identified that, regardless of core temperature status, runners presented with significant changes in kinetic measures across the race with increases in shock, impact *g*, and braking *g* values. We believe these findings may be attributed, in part, to lower limb muscular fatigue and reduced ability to attenuate force toward later race stages.[30] Previous research exploring longer-distance road race biomechanics with wearable sensors identified similar increases in peak lower extremity accelerations and subsequent loading rates in later race segments.[23] The use of in-lab wearable sensors for biomechanical assessments have similarly reflected this relationship between fatiguing endurance exercise and heightened lower limb accelerations and ground reaction forces during running.[9,15] Although the race duration in the present study was substantially shorter than previous investigations, these findings corroborate that high-intensity running reflected in racing demands often lead to fatigue-related kinetic changes among runners.

Limitations

Our study was conducted at a single assessment timepoint, and, as such, we were not able to assess a wider range of core temperature and biomechanical response relationships. Furthermore, due to logistical difficulties of sensor ingestion wait time and reliable core temperature measures, we were unable to obtain concomitant biomechanical and core temperature data during VO_2max assessments. We did not assess for heat acclimation among participants; however, this may have influenced the core temperature and subsequent movement pattern findings. While wearable technology often presents many solutions for real-world monitoring, there are sometimes drawbacks in technology functionality, reflected in the 7 drop-out cases due to ingestible thermometer error. Our study sample consisted primarily of middle-aged adults and may not be generalizable to other populations. We did not explicitly assess athletes' footwear; footwear shock attenuation may be influenced by environmental conditions, although this is most pronounced in cold weather cases.[16]

CONCLUSION

While runners presented with increased core temperatures, and increased sensor-derived shock, impact *g*, and braking *g* values over the duration of an 11.27-km road race, these thermal and biomechanical changes were not significantly related. Observed kinetic changes may be related to other intrinsic factors, such as muscular fatigue over the duration of the race. Within-runner spatiotemporal changes were not observed in relationship to core temperature changes and may instead be more sensitive to other environmental factors.

CLINICAL RECOMMENDATIONS

- Clinicians may not expect changes in biomechanical movement patterns to signal thermal responses during outdoor running in a singular event (Level of evidence, 2).
- Clinicians may expect that kinetic changes across a race may be attributed to other contextual factors, such as neuromuscular fatigue (Level of evidence, 2),

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