

Dynamic Postural Stability in Active, Adolescent Males Following Repeated Bouts of Aerobic Exercise in Hot and Temperate Environments: A Pilot Study

Colin W. Bond, MS*; Jason C. Dorman, MS*; Lisa N. MacFadden, PhD*; Thayne A. Munce, PhD*

ABSTRACT Introduction: Proper jump-landing neuromuscular control is crucial in mitigating lower-extremity musculoskeletal injuries. The presence of fatigue, especially in extreme environments, may degrade dynamic postural stability (DPS) and result in lower-extremity injuries. This study aimed to evaluate the influence of moderate intensity exercise in hot (HOT) and temperate (TEMP) ambient temperatures and residual effects of a previous bout on DPS during a single-legged jump-landing. It was hypothesized that the participants would display worse DPS after HOT compared to TEMP. Methods: Six recreationally active young males (16.8 ± 0.7 year, 1.88 ± 0.12 m, 83.8 ± 19.8 kg) completed two, 60-minute bouts of exercise with 60 minutes of rest between bouts in both HOT (35°C) and TEMP (22.2°C). Heart rate and core body temperature (T_c) were monitored continuously, and DPS was assessed before and after each bout. Results: The DPS time and condition effects were not identified ($p > 0.05$), but HOT elicited some notable ($d > 0.20$) increases in heart rate, T_c , and DPS compared to TEMP. Conclusions: The DPS decrements varied between subjects suggesting individual-specific etiology. Repeated bouts of exercise in HOT may place an individual at a greater risk for injury than TEMP if proper prevention strategies are not used.

INTRODUCTION

Musculoskeletal injuries are common in the military and occur in training, garrison, and theater. The injuries can have long-term consequences, including an elevated risk of reinjury.¹⁻⁵ Each year, approximately 50% of active duty personnel sustain a musculoskeletal injury with about 25% of those sustaining a second injury.⁵ These injuries may result in clinic visits or hospitalizations, disability dischargers, loss of duty days, and a negative impact on the readiness of the military.^{1-3,5} Identifying risk factors related to these injuries may enable US military personnel to implement effective injury prevention measures. In doing so, military members may experience a reduced incidence of musculoskeletal injury and enhanced performance.

Jumping and landing, often intermixed with repetitive locomotor tasks such as running, are common activities for service members. Proper neuromuscular control during these activities is crucial in preventing the aberrant motion association with musculoskeletal injury. Dynamic postural stability (DPS) is one measure of neuromuscular control and may serve as a surrogate measure of the capacity of the lower-extremity neuromuscular system to achieve stability during a shift from

a dynamic movement to a stationary position over the base of support.⁶⁻⁸ DPS-related risk factors may be particularly relevant to military service members who report a high frequency of knee/lower leg injuries as a result of tasks including lifting and carrying heavy loads, dismounted patrolling, and physical training.¹⁻⁵

Although strenuous exercise in hot and humid environments is associated with several health concerns,⁹ a potential influence on musculoskeletal injury risk has not been thoroughly explored.^{10,11} This has relevant implications for military service members since they routinely operate in hot and humid environments. Physical activity in these environments combined with standard clothing and gear worn by military service members may not allow for proper heat dissipation, causing core body temperatures (T_c) to rapidly rise. Literature has demonstrated that elevated T_c greater than 40°C may cause central nervous system dysfunction that reduces voluntary activation of skeletal muscle¹²⁻¹⁴ and that these reductions may be more discernable during dynamic contractions compared to isometric contractions.¹⁵ Ultimately, these central nervous system impairments combined with the fatigue associated with physical activity¹¹ may transiently degrade an individual's ability to safely control movement, leading to a compromised DPS and the manifestation of aberrant movements associated with musculoskeletal injury.^{10,16,17}

Perhaps one of the largest challenges facing military service members is engaging in physical activity multiple times per day. Unfortunately, little is known about the residual effects of previous bouts of physical activity and appropriate recovery times between bouts that would allow them to engage in physical activity safely and optimally again on the same day, especially in hot and humid environments. Thus, the purposes of this study were to evaluate the influence

*Sanford Sports Science Institute, Sanford Health, 2215 W Pentagon Pl, Sioux Falls, SD 57107

†Guarantor: Lisa MacFadden

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of intermittent, moderate intensity exercise in hot (HOT) and temperate (TEMP) environments on DPS, and the potential confounding effect of residual fatigue on DPS during repeated bouts of exercise in these environmental conditions. It was hypothesized that repeated bouts of exercise in HOT would elicit larger decrements in DPS compared to TEMP.

METHODS

This study used a randomized, cross-over design to determine the effect of repeated bouts of exercise in HOT and TEMP on DPS. Eight, regularly active young male subjects (16.8 ± 0.7 year, 1.88 ± 0.12 m, 83.8 ± 19.8 kg, 64.1 ± 8.6 mL · kg⁻¹ · min⁻¹ VO_{2peak}) were recruited to participate in this study. Only six of the eight participants successfully completed all of the study's assessments. All subjects were actively participating in organized sports or physical activity at least two times per week and likely had comparable levels of fitness to military service members given their mean VO_{2peak}. The Sanford Health Institutional Review Board approved (approval # 03-11-019) the study's protocol, and all participants were informed about the experimental procedures, risks, and benefits before providing their informed written consent or assent to participate. Parental or guardian consent and assent of the participant were obtained if the participant was ≤ 17 years.

Day 1

Participants' VO_{2peak} was determined using indirect calorimetry (VMax Encore 29, Care Fusion, Yorba Linda, California) so individualized workloads could be prescribed for the exercise protocols. A modified Astrand protocol was used to determine VO_{2peak}, which consisted of running on a treadmill at a personalized constant speed and initial grade of 0%, with subsequent 2.5% increases in grade every 2-minute until voluntary exhaustion occurred. The assessment was performed in an ambient temperature of approximately 22.2°C with 50% relative humidity. Each participant's maximal, single-legged forward jump distance was assessed on the dominant leg with shoes on so the jump distance for the DPS assessment could be individualized. Participants were instructed to stand on their dominant leg with their arms crossed against their chest, jump forward as far as they can, and "stick" the landing. Finally, participants were familiarized to the DPS assessment by performing the procedure, which is explained below, until they were comfortable.

Days 2 and 3

Two repeated exercise bouts were performed in a randomized order, separated by 1 week, and completed at identical times of the day. Exercise and DPS assessments were completed in an environmental chamber (Environmental Growth Chambers, Chagrin Falls, Ohio), where temperature and relative humidity were constantly maintained, though the ambient temperature was randomized between trials. The HOT and TEMP con-

ditions were completed in ambient temperatures of 35 and 22.2°C, respectively, with relative humidity set to 50% for both conditions.

A temperature sensor (CorTemp™ 2000, HQ, Inc., Palmetto, Florida) was ingested eight to 12 hours before each visit. Participants were highly encouraged to consume an identical breakfast for each visit prior to arriving at the laboratory consisting of a plain bagel with light topping, 12-oz of fruit juice, and a granola bar; though, adherence to this is unknown. Participants wore identical athletic clothing for each condition, which included shorts, top (t-shirt/tank top), socks, and athletic shoes. Participants were outfitted with a wireless heart rate (HR) monitor worn around the chest (Polar® T31, Lake Success, New York). They then entered the environmental chamber and rested stationary for 5 minutes to passively acclimate to the environmental condition. Resting HR, T_c, and DPS measurements (PRE 1) were obtained before the start of exercise.

Each 60-minute bout of exercise was comprised of six, 10-minute periods in which the participant performed 8 minutes of moderate intensity, continuous exercise followed by 2 minutes of passive rest. Participants performed a sequence of running and cycling at a calculated target intensity of 60 and 40% of VO_{2peak}, respectively, in the following order: running-cycling-running, running-cycling-running. Upon completion of the first exercise bout (BOUT 1), participants were reassessed for DPS (POST 1) and passively rested (seated) for 60 minutes outside of the environmental chamber in an ambient temperature of approximately 22.2°C. At the conclusion of the 60-minute recovery period, participants reentered the environmental chamber to passively acclimate for 5 minutes before being reassessed for DPS (PRE 2). A second, 60-minute exercise bout was completed using a prescription of running and cycling identical to BOUT 1. At the conclusion of the second bout of exercise (BOUT 2), participants were assessed for DPS for a final time (POST 2) followed by a 15-minute passive recovery period outside of the environmental chamber.

Participants consumed water throughout the 60-minute exercise bouts using an identical hydration prescription for both environmental conditions. Up to 15 mL of water per kg of body mass was available for drinking during each bout with total fluid consumption evenly divided into seven scheduled times per bout. During the 60-minute recovery period, participants received a specific volume of water equivalent to 130% (by mass) of the total sweat loss incurred during BOUT 1, which was calculated as the sum of PRE 1 body weight minus POST 1 body weight plus total fluid intake during BOUT 1. Participants also consumed one granola bar during the 60-minute recovery period between BOUT 1 and BOUT 2.

Dependent Variables

Participants' body mass was recorded PRE and POST BOUT 1 and 2, with changes serving as an indicator of hydration

status. For each body mass assessment, participants wore identical dry shorts only so their measured body mass was minimally effected by the accumulation of sweat on their clothing. Core body temperature (T_c) and HR were recorded every 2 and 1 minutes, respectively, throughout BOUT 1, recovery, BOUT 2, and the follow-up period. Mean and peak T_c were used as an indicator of thermal strain, which is associated with central nervous system dysfunction when it rises from baseline above critical levels.^{12–15} Mean and peak HR were used as a measure of cardiovascular strain. An increase in cardiovascular strain leads to decreases in central blood volume and stroke volume and a concomitant rise in HR.^{12–15}

DPS assessments were completed using an in-ground three-dimensional force plate (OR6, AMTI, Watertown, Massachusetts) sampling at 100 Hz. Similar sampling rates have demonstrated appropriate sensitivity for measurements of DPS.^{6,7,18} The DPS assessments were completed on the dominant leg, which was determined as the leg the participant indicated he would kick a soccer ball with, with shoes on. Participants completed three trials of the single-legged, forward jump-landing at a distance equal to 60% of their maximal single-legged, forward jump distance (Fig. 1). Participants were instructed to stand on the dominant leg with their arms crossed against their chest, jump forward so they landed on their dominant foot in the middle of the force plate, stabilize as quickly as possible, and remain motionless for the remainder of the 20-second sampling period. Kinetic data sampling was initiated when the participant began their jump. Improperly performed trials were discarded, and an additional trial was completed. Only the dominant limb was tested due to time constraints, and previous literature has indicated that poor time to stabilization (TTS), a measure of DPS, is individual-specific and not a leg-specific phenomenon.¹⁸ Vertical ground reaction force (vGRF) data were filtered post hoc using a 2nd order Butterworth filter with a cut-off frequency of 12 Hz.⁷ Subjects' DPS was quantified as TTS, which is the time required for the vertical GRF component to reach and remain within $\pm 5\%$ of the participant's body mass for 1-second after landing (Fig. 2).^{8,18} The mean TTS from all three trials was used for analyses.

Statistical Analyses

Statistics were completed using a statistic program (Graph Pad, La Jolla, California). Descriptive statistics including means, standard deviations (SD), and 95% confidence intervals (CI) were calculated to examine participant's physical characteristics and the dependent variables. A two-way repeated measures analysis of variance was used to assess for the effects of time and condition, and Bonferroni corrected pairwise comparisons were used where appropriate to evaluate the source of identified effects. Significance was initially set to $p < 0.05$.

Standardized effect size (d) was used to further evaluate the practical differences in the dependent variables of TTS,

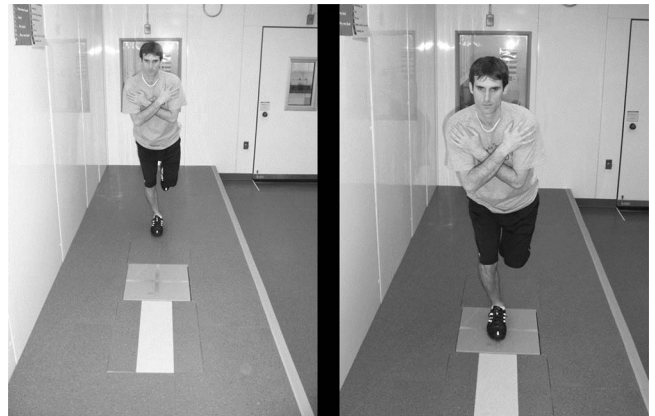


FIGURE 1. Single-legged jump-landing task completed PRE and POST BOUT 1 and 2 of exercise. The single-legged, forward jump-landings were completed at a distance equal to 60% of their maximal single-legged, forward jump distance. Participants were instructed to stabilize as quickly as possible and remain motionless upon landing.

HR, and T_c between conditions at single time points using the following equation:

$$d = \frac{M_a - M_b}{S} \quad (1)$$

where M_a and M_b are condition means, and S is the pooled SD.¹⁹ A small effect size was present if $d \geq 0.20$, a medium effect was present if $d \geq 0.50$, and a large effect was present if $d \geq 0.80$. An effect size was considered trivial if $d < 0.20$.

Within-day reliability of PRE 1 TTS on day 1 and day 2, which was either HOT or TEMP and randomized between participants, was assessed by means of typical error (TE) calculated using the following equation:

$$TE = \sqrt{\left(\sum SD^2/n_{\text{subject}}\right)} / \sqrt{n_{\text{trials}}} \quad (1)$$

where SD represents the within-subject SD for three trials.^{20,21} Between-day reliability of PRE 1 TTS was also assessed using the abovementioned equation, though this reliability assessment should be interpreted with caution since the protocol in the 5 minute immediately prior to the PRE 1 assessment involved an acclimation period in the respective HOT or TEMP environment. Still, it is likely a reasonable assessment for this study since no exercise was completed during this acclimation period.

RESULTS

The participants' T_c during HOT and TEMP are presented in Figure 3A. Starting with the first acclimation and ending after the 15-minute recovery period, participants demonstrated a greater mean T_c for HOT compared to TEMP (37.8 ± 0.6 vs $37.5 \pm 0.3^\circ\text{C}$, respectively, $d = 0.73$). Participants' T_c at PRE 1 prior to initiating the exercise protocol was in a normal range for both HOT and TEMP (37.1 ± 0.3 vs

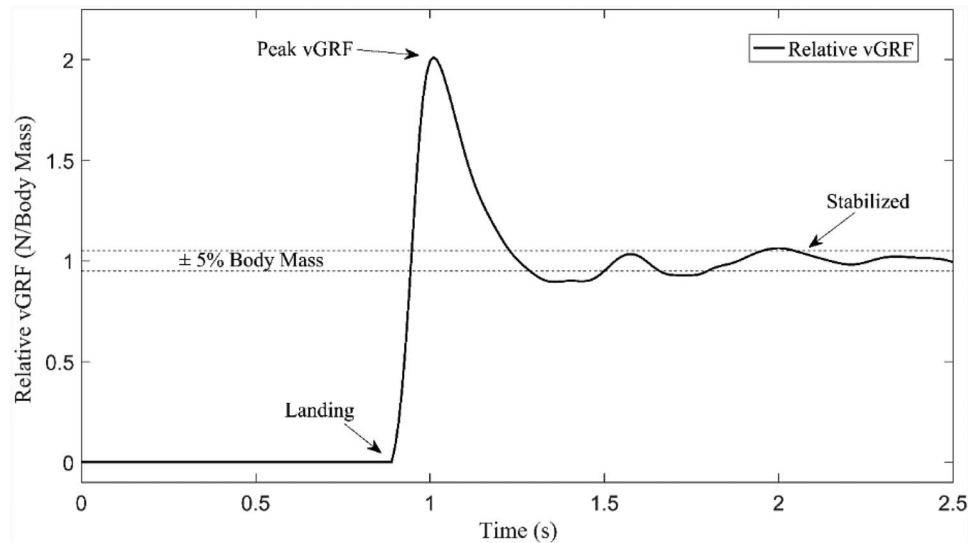


FIGURE 2. Example of vGRF—time curve for the single-legged forward jump-landing. TTS was calculated the time required for vGRF to reach and remain within $\pm 5\%$ of the participant's body weight for 1 second after landing.

$36.9 \pm 0.3^\circ\text{C}$, respectively), though medium effects were identified between conditions ($d = 0.46$). During BOUT 1, peak T_c was greater in HOT compared to TEMP (38.7 ± 0.6 vs $37.9 \pm 0.3^\circ\text{C}$, respectively; $d = 1.90$). After the 60-minute recovery period at PRE 2, T_c returned to normal temperatures nearly identical to PRE 1 for both HOT and TEMP (37.0 ± 0.3 vs $37.0 \pm 0.2^\circ\text{C}$, respectively; $d = 0.0$). During BOUT 2, peak T_c was again greater in HOT compared to TEMP (38.7 ± 0.2 vs $37.9 \pm 0.2^\circ\text{C}$, respectively; $d = 3.50$).

The participants' HR during HOT and TEMP are displayed in Figure 3B. Starting with the first acclimation and ending after the 15-minute recovery period, participants demonstrated a greater mean HR for HOT compared to TEMP (126 ± 37 vs 111 ± 32 beats per minute [bpm], respectively; $d = 0.43$). Participants' HR at PRE 1 prior to initiating the exercise protocol was in a normal range for both HOT and TEMP (77 ± 3 vs 70 ± 6 bpm, respectively), though large effects were identified between conditions ($d = 1.42$). During BOUT 1, peak HR was greater in HOT compared to TEMP (177 ± 8 vs 155 ± 6 bpm, respectively; $d = 3.39$). After the 60-minute recovery period at PRE 2, HR returned to normal levels comparable with PRE 1 for both HOT and TEMP (75 ± 7 vs 69 ± 9 bpm, respectively), though medium effects were present between conditions ($d = 0.74$). During BOUT 2, peak HR was again greater in HOT compared to TEMP (179 ± 7 vs 157 ± 8 bpm, respectively; $d = 2.30$).

Mean PRE 1 TTS on day 1 and day 2 was 0.80 second (95% CI [0.59–1.01]) and 0.87 second [0.56–1.18] ($d = 0.27$), respectively, which was either HOT or TEMP and randomized between participants. Within-day PRE 1 TTS TE was 0.09 second for day 1 and 0.29 second for day 2. Between-day PRE 1 TTS TE was 0.11 second. The cohort's TTS at PRE and POST 1 and 2 during HOT and TEMP are depicted in Figure 4, whereas Figure 5A and B display the participants' individual HOT and TEMP TTS, respectively. The two-way repeated

measures analysis of variance indicated that there was no significant interaction of time and condition ($F(3,15) = 0.824$, $p = 0.501$, $\eta^2 = 0.01$), nor significant effects of condition ($F(1,5) = 6.47$, $p = 0.052$, $\eta^2 = 0.04$) or time ($F(3,15) = 1.67$, $p = 0.216$, $\eta^2 = 0.08$) on TTS. Between HOT and TEMP, small standardized effects for the means were identified at PRE 1, POST 1, and PRE 2 ($d = 0.31$, 0.24, and 0.33, respectively), and medium standardized effects were identified at POST 2 ($d = 0.59$).

DISCUSSION AND IMPLICATIONS

Poor DPS during a single-legged jump-landing task is a likely risk factor for musculoskeletal injury,¹⁸ and an individual's TTS could be compromised by fatigue.^{22,23} Physical activity in hot and humid environments may further exacerbate these decrements.¹⁰ Repeated bouts of exercise in these environments are physiologically straining and challenge the body's thermoregulatory processes^{9,24,25} resulting in a reduction in voluntary neuromuscular activation,^{12–14} which may be contributory to an individual's risk of sustaining a musculoskeletal injury. It was hypothesized that repeated bouts of exercise, consisting of moderate intensity running and cycling, in HOT would elicit larger increases (decrements) in TTS compared to TEMP. The authors recognize that the sample size is small and that the study's conclusions are necessarily speculative due to inadequate statistical power; though, there are some meaningful discoveries and suggestions for future research addressing this poorly understood topic.

No statistically significant time or condition effects on TTS were identified; however, medium standardized effects were identified between HOT and TEMP conditions at POST 2 (Fig. 4). This may suggest that repeated bouts of exercise in HOT cause larger decrements in TTS than in

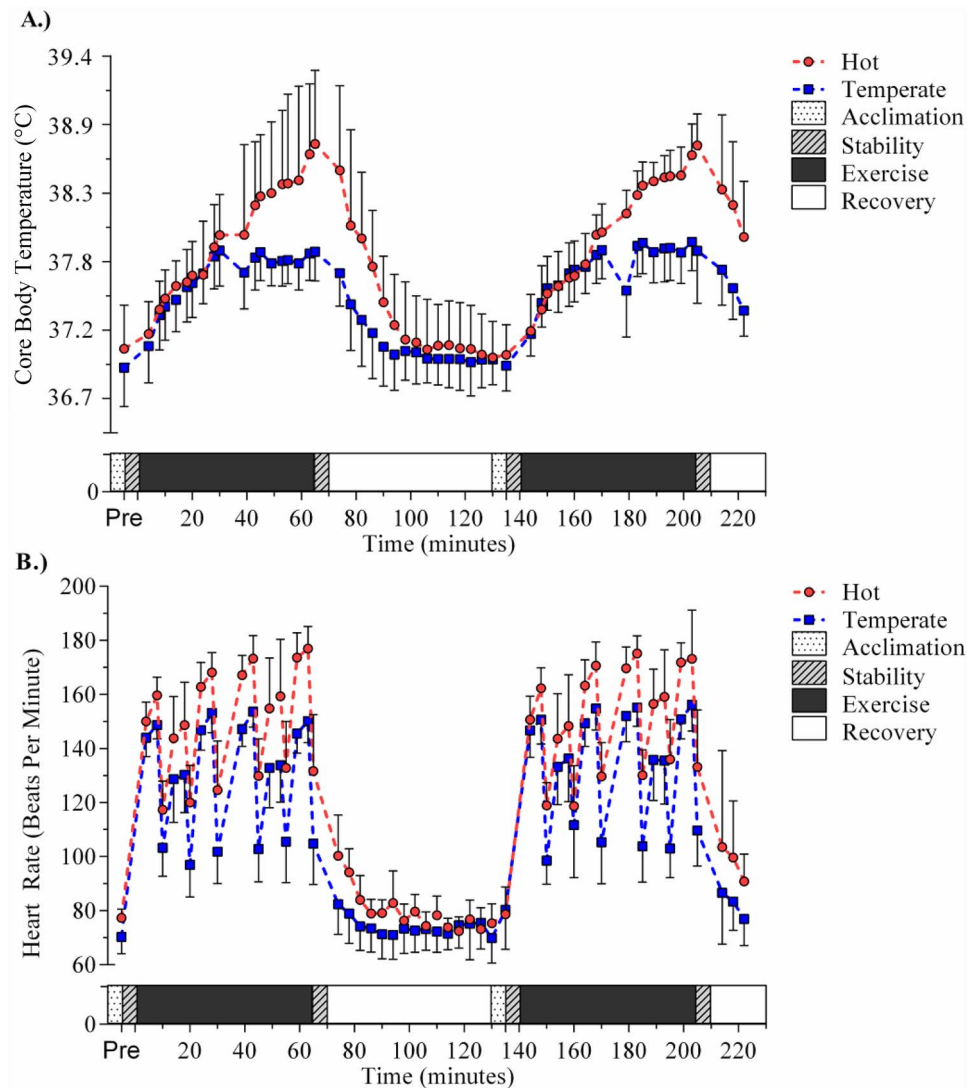


FIGURE 3. (A) Participants' core body temperature ($^{\circ}\text{C}$) in the temperate (TEMP) (blue squares) and hot (HOT) (red circles) conditions over the duration of the repeated bout exercise protocol. (B) Participants' HR (beat per minute) in the temperate (TEMP) (blue squares) and hot (HOT) (red circles) condition over the duration of the repeated bout exercise protocol. Data expressed as mean \pm SD. $N = 6$.

TEMP and that the POST 2 effects were caused by residual fatigue from BOUT 1 since there were smaller standardized effects between conditions at POST 1. Alterations in TTS are highly variable between participants with some participants seeming to be more affected than others, which indicates that DPS responses to fatigue are likely influenced by several individual-specific factors (Fig. 5). Research has demonstrated individual variations in susceptibility to heat intolerance with exercise because of predisposing factors such as insufficient physical fitness or partial heat acclimatization.^{9,26–28} Data collection for this study lasted from July to February in the northern hemisphere in a region with a humid continental climate, meaning that some participants may have been more adequately acclimatized to exercise in the heat if they completed their bouts in the summer compared to the winter. Although this may have contributed to the between-

subject variation in TTS responses, this was not investigated. Additionally, the rate of recovery of T_c and HR may serve as physiological indicators of how well acclimatized an individual is; though, this was also not investigated. Heat acclimatization has implications to military service members, especially new members or those who may be operating in new and/or extreme environments. Even military service members who are adequately acclimatized may be susceptible to critical thermal and cardiovascular strain given the right combination of environmental conditions and other factors associated with the rate of heat storage or dissipation (eg, fitness, clothing, etc.).

The participants' T_c increased at a similar rate in HOT and TEMP from PRE 1 to approximately 30 minute of both BOUT 1 and 2, though T_c continued to rise in HOT and leveled off in TEMP for the final 30 minute of each bout, ultimately

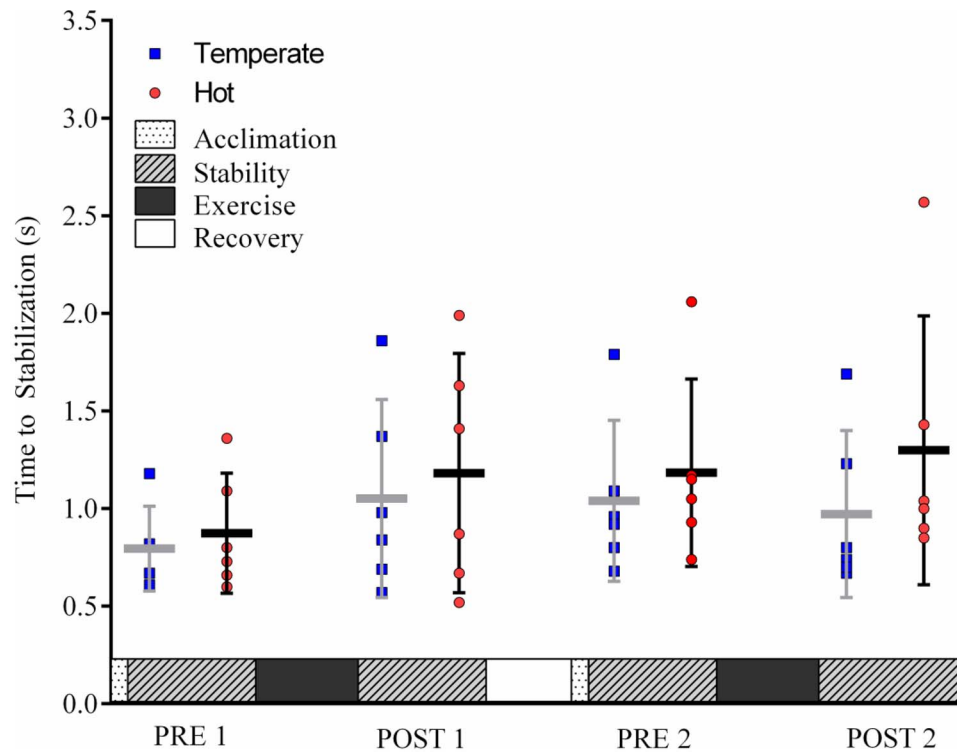


FIGURE 4. TTS (seconds) at PRE and POST BOUT 1 and 2 in the temperate (TEMP) (blue squares) and hot (HOT) (red circles) blue and red, condition. Representation of acclimation, stability, exercise, and recovery events occurring between assessments not drawn to scale. Standardized effects (*d*) between conditions: PRE 1 = 0.31, POST 1 = 0.24, PRE 2 = 0.33, POST 2 = 0.59. Solid bars: condition means; whiskers: 95% CI. *N* = 6.

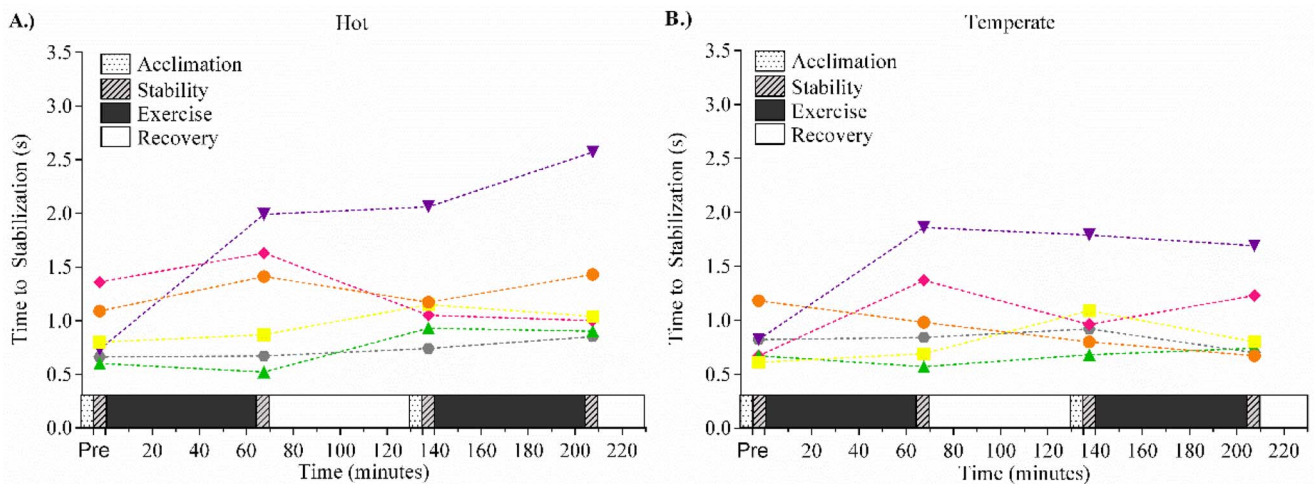


FIGURE 5. (A) Individual participants' TTS (seconds) at PRE and POST BOUT 1 and 2 in the hot (HOT) condition. (B) Individual participants' TTS (seconds) at PRE and POST BOUT 1 and 2 in the temperate (TEMP) condition. Colored symbols used to denote individual participants are identical between figures for the same participant.

resulting in large standardized effects between conditions (Fig. 3). It is possible that the approximate 1.7°C rise in T_c from PRE to POST during BOUT 1 and BOUT 2 in HOT may not have been large enough to cause central nervous system dysfunction, which may in part be why no statistically significant effects on TTS were identified between HOT and TEMP. Longer duration or more strenuous bouts of exercise in

HOT may have elicited increases in T_c of 2°C or more above baseline, which appears necessary to cause a notable nervous system dysfunction that may affect an individual's ability to stabilize quickly.¹²⁻¹⁴ The participants' T_c and HR returned to baseline levels comparable with PRE 1 at the conclusion of the 60-minute recovery period for the PRE 2 assessment, which was an unexpected finding. Thus, a shorter recovery period

between bouts may be needed for the residual effects of BOUT 1 to carry over to BOUT 2. Similar peak T_c and HR between BOUT 1 and BOUT 2 in each respective condition supports this conclusion. The participants in this study were wearing relatively minimal clothing. Military service members are often outfitted with clothing that may not allow for efficient heat dissipation. In this context, T_c may rise above critical levels more rapidly and stay elevated longer than what was demonstrated here.

Even though it was attempted to evaluate the detrimental effects of repeated bouts of exercise in hot and humid environments on DPS, we most likely demonstrated a best-case scenario. Participants consumed fluid at a standardized rate and volume throughout the exercise protocol, which has been shown to blunt the rise in T_c during exercise in the heat.^{29,30} DiStefano et al. demonstrated that hyperthermia combined with hypohydration elicited larger decrements in postural control and movement quality than hyperthermia and euhydration.¹⁰ It is possible that if the participants in this study drank fluids ad libitum, they would have become voluntarily dehydrated and their T_c would have approached 40°C in HOT. The participants in this study were also removed from HOT and rested in a normothermic environment while stationary during the recovery period, which may have assisted in the rapid restoration of T_c to baseline levels following BOUT 1. Further, subjects consumed a small snack between BOUT 1 and BOUT 2, which may have aided in preventing hypoglycemia-associated central nervous system impairments during BOUT 2. Military service member may not have the same access to fluids, normothermic environments, or sources of macronutrients during their missions. Additionally, potentially injurious decrements in TTS because of fatigue may not be fully manifested until sufficiently difficult jump-landing tasks are used. Military service members are often lifting and carrying heavy loads^{1–5} and have large cognitive demands, which could have a negative influence on neuromuscular control and increase the risk for musculoskeletal injury.^{31–34}

This study was not without limitations, most notably low statistical power and the inclusion of only males. The rather modest rise in T_c during HOT was most likely due to the limited intensity and duration of the exercise protocol, the effort to keep the participants euhydrated, and the availability of an optimal recovery environment between bouts. Measures of central fatigue, such as an electrically evoked twitch interpolation during a maximal voluntary contraction, were not obtained;³⁵ thus, the degree of central fatigue experienced by the participants is uncertain. Although the exercise protocol used in this study may have caused a notable level of general fatigue, it lacked dynamic, multiplanar movements similar to the tasks a military service member may engage in; therefore, the ecological validity of the fatigue protocol is unclear.^{36,37} Only the dominant limb was tested in this study using a single-legged jump-landing from a forward direction. Future work should include an assessment of DPS on both the dominant and nondominant leg from a variety of jump directions as

there may be interlimb or jump direction differences in motor control responses to exercise. The DPS measures such as TTS can be calculated using a variety of thresholds, sampling rates, and data filtering techniques, which can limit interpretation of TTS values obtained from different studies.³⁸ The TTS method only utilizes the vertical component of the GRF. It is possible that other measures of DPS, such as the DPS index, may provide a more comprehensive evaluation of DPS as it utilizes GRF in three planes.⁶

CONCLUSIONS

Although this study's findings are limited due to the sample size, the hypothesis is partially supported because DPS was compromised after exercise bouts in a hot and humid environment, though the residual effects of a previous bout did not carry over to the second bout. It is possible that repeated bouts of exercise in HOT may place an individual at a greater risk for injury than TEMP by increasing the manifestation of aberrant motion associated with musculoskeletal injury. This may be detected using TTS during a single-legged jump-landing. Decrements in TTS vary between subjects suggesting individual-specific etiology and thermoregulatory responses. Proper musculoskeletal injury prevention strategies should include not only neuromuscular training and movement education, but sufficient heat acclimatization, adequate time in a normothermic environment between exercise bouts to fully recover, and access to ample fluids to remain euhydrated.

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