IMPACT OF HEAT STRESS AND COOLING STRATEGIES ON BODY TEMPERATURE AND PERFORMANCE IN ELITE TENNIS PLAYERS

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ABSTRACT

Tennis matches are intense, of long induration, with brief recovery periods, played in hot environments. This subjects elite tennis athlete to heat stress. Whether high core temperature impacts performance, and whether performance decrements are attenuated with cooling, remains unknown. Three studies evaluated heat stress on rectal temperature (T_{re}), skin temperature (T_{sk}) and shot accuracy (SA) after performing high intensity exercise at 22 °C and 38 °C and relative humidities of 31% and 38% respectively. Study 1 compared T_{re}, $T_{sk,}$ SA in a temperate environment (TE) and a hot environment (HOT). HOT trial T_{re} (38.5 ± 0.4 °C) and T_{sk} (35.0 ± 1.6 °C) were higher than TE (37.8 ± 0.7 °C and 32.0 ± 1.3 °C, respectively). SA decreased (p = 0.003) between TE [57.5 ± 17.9 au out of 100] and HOT (33.4 ± 4.0 au), with greatest reduction in players with highest scores. Study 2 examined cooling of abdominal walls and thighs during rest periods and recovery on $T_{re,}$ SA. T_{re} increased between start and end of both trials (p < 0.008). Treatments didn't mitigate increased T_{re}. Treatment SA increased (p < 0.05). Study 3 evaluated continuous cooling device (vest) plus ice-pack applications on thighs, during rest periods in the high intensity protocol and recovery in hot condition verses control on $T_{re,}$ SA. A significant time by condition effect for T_{re} (p < 0.05). T_{re} at end of high intensity protocol in control was 38.3 ± 0.6 °C. T_{re} at end recovery in control was 38.4 ± 0.4 ° C. No difference between T_{re} at start of treatment condition (37.5 ± 0.6 °C) and end of high intensity exercise (38.0 ± 0.7 °C). T_{re} at the end of recovery (37.0 ± 1.4 °C) was lower than Tre at end of high intensity exercise (p < 0.008). $T_{re\ at}$ the end of recovery in control was higher than T_{re} at end of recovery in treatment. SA increased in treatment condition versus control [(p < 0.05) and large effect size (Cohen's d = 1.38)]. Combined cooling mitigated the rise of T_{re} and increased SA in elite tennis athletes.

DEDICATION

This manuscript is dedicated to tennis players, in that it may protect their health and safety and hopefully improve their performance.

LIST OF ABBREVIATIONS & SYMBOLS

α	alpha
BL	Baseline
°C	Degrees Celsius
cm	Centimeters
ES	Effect Size
°F	Degrees Fahrenheit
HOT	Hot Trial
ICE	Treatment trial w/ ice applications intermittently applied to the core and thighs
kmph	Kilometers per hour
kg	Kilograms
m	Meter
p	Probability associated with the occurrence under the null hypothesis of a value as extreme as or more extreme than the observed value
r	Pearson product-moment correlation
rH	Relative humidity
RPE	Rating of Perceived Exertion
SA	Shot Accuracy
T_c	Core Temperature
$T_{re}EndHOT$	Ending rectal temperature of the hot condition
$T_{re}EndTE$	Ending rectal temperature of the temperate condition

$T_{re}ExEndICE$	Ending rectal temperature of exercise phase of the heat with ice condition
$T_{re}ExEndHOT$	Ending rectal temperature of exercise phase in the hot condition
$T_{re}ExHOT$	Ending rectal temperature of exercise phase in the hot condition
$T_{re}ExVEST$	Ending rectal temperature of exercise phase in the heat with vest condition
$T_{re}RecVEST$	Ending rectal temperature of recovery phase in the heat with vest condition
$T_{re}RestEndHOT$	Ending rectal temperature of resting phase in the hot condition
$T_{re}RecHOT$	Ending rectal temperature of recovery phase in the hot condition
$T_{re}StartICE$	Starting rectal temperature of the heat with ice condition
$T_{re}StartHOT$	Starting rectal temperature of the hot condition
$T_{re}StartVEST$	Starting rectal temperature in the heat with vest condition
$T_{re}StartTE$	Starting rectal temperature of the temperate condition
TE	Temperate Trial
T_{sk}	Skin Temperature
$T_{sk}EndHOT$	Ending skin temperature of the hot condition
$T_{sk}EndVEST$	Ending skin temperature of exercise phase in the heat with vest condition
$T_{sk}EndTE$	Ending skin temperature of the temperate condition
$T_{sk}ExEndICE$	Ending skin temperature Exercise Phase in the heat with ice condition
$T_{sk}ExEndHOT$	Ending skin temperature of Exercise Phase in the hot condition
$T_{sk}ExHOT$	Ending skin temperature of Exercise Phase in the hot condition
$T_{sk}RecVEST$	Ending skin temperature of Recovery phase in the heat with vest condition
$T_{sk}RestEndICE$	Ending skin temperature of Resting Phase in the heat with ice condition
$T_{sk}RestEndHot$	Ending skin temperature of Resting Phase in the hot condition

$T_{sk}StartICE$	Starting skin temperature in the heat with ice condition
$T_{sk}StartHOT$	Starting skin temperature of the hot condition
$T_{sk}StartVEST$	Starting skin temperature in the heat with vest condition
$T_{sk}StartTE$	Starting skin temperature of the temperate condition
VEST	Treatment trial with continuous wearable vest and ice applications to thighs
$<$	Less than
$=$	Equal to

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CHAPTER 1

INTRODUCTION

Elite tennis matches are often played in hot environments, which can affect health, safety and performance (34). In fact, excessive heat stress in major international events has forced some elite tennis athletes to withdraw from competition, while inducing related illnesses in others (4). Furthermore, some of the top players in the world have reported that high ambient temperatures negatively affected their performance (2, 3, 4). Specifically, ambient temperatures remained between 41.5 °C and 43.9 °C for 5 consecutive days at the Australian Open in 2014, spawning comments from players related to their feelings of "life-threatening" or "inhumane" situations (2, 3). The extremely high environmental temperatures at the event resulted in a record number of withdrawals from competition and dozens of heat illnesses occurring to players, staff and spectators (4).

Heat strain in tennis is a global issue, as average temperatures in cities where elite tennis events are typically held have shown an increasing trend (12). For instance, average temperatures in Melbourne, Paris, New York, and London (i.e., the "Grand Slam" cities) have risen at a rate of 0.69°F, 1.26°F, 0.56°F, and 0.68°F, respectively, per decade since 1968 (12). Moreover, competitors are playing with greater quality and an increased level of fitness compared to previous years. This is resulting in extended match durations and longer exposures to hot environments. Because of these factors, the International Tennis Federation (ITF) has recently acknowledged the dangers of heat stress by issuing health and safety guidelines to prevent related illnesses (4).

However, much of the awareness regarding heat challenges in tennis has come from anecdotal reports in mainstream publications. Scientific study related to this area in tennis is limited, as the aims of most of the previous research on heat stress in sports has focused on runners and cyclists (6, 29, 30). Because tennis is uniquely different from running and cycling, the findings of previous studies may not be fully applicable. Therefore, more research is needed to improve the standards associated with preventing heat illnesses in the sport. The purpose of this dissertation was to examine the potential effects of heat stress on performance of tennis players. A secondary aim was to examine the potential mitigating effects of practical cooling strategies for the sport of tennis.

Potential consequences of heat stress in tennis

Physiological heat production comprises 70-80% of metabolism, with only 20-30% directed toward bioenergetics (44). The result is a core body temperature (T_c) that is typically maintained between 36.1 to 38.8 °C under normal conditions (44). The balance between heat gain and heat loss occurs through four avenues of heat exchange: radiation – heat loss or gain in the form of waves; conduction – heat gain or loss through surface contact; convection – heat gain or loss resulting in from movement of a fluid (water or air) across the body surface (44) and evaporation – heat loss through evaporation of sweat.

At rest in temperate conditions, most heat loss occurs via radiation. However, when T_{re} increases, during exercise or when exposed to a hot environment, evaporation is primarily responsible for the removal of heat. This takes place by the pre-optic anterior hypothalamus

(POAH) in the brain, functioning similar to the "thermostat" in a home, monitoring increases in temperature in order to maintain thermostasis (41). The set point in humans is 37 ºC (44). Inputs into monitoring centers in the POAH derive from receptors located in the core and the periphery (including the skin) which can detect temperature increases (44). Upon detection of an increase in temperature, the POAH initiates efferent nerve stimulation that activates the sweat glands (44). Simultaneously, the vasomotor control center withdraws vasoconstrictor tone to the skin promoting increased blood flow via vasodilation, delivering the heat to the skin for the removal to the outside environment (44).

During intense exercise of long duration heat must be released to the environment to maintain core temperatures within an acceptable range. When the body's heat gain exceeds the body's heat loss, as it does in prolonged moderate to heavy exercise in hot conditions, a heat storage results. Heat storage causes body temperatures to rise; therefore, it is widely accepted that prolonged athletic activity of moderate-to-high intensity played in a hot environment results in heat storage causing an increase in core temperature. If not mitigated such elevated core temperatures may lead to performance decrements, heat illness, and in some instances death.

This high thermal load combined with high metabolic rates results in high core temperatures (i.e. 38 – 40 °C) (44). Hyperthermia may result in exercise impairments that negatively may affect performance and expose athletes to the dangers of heat illnesses (37). High core temperatures have also been shown to impair motor muscle activation (44), decrease the central drive to exercise (44), and be related to fatigue (17, 31, 42, 44). Additionally, thermoregulatory mechanisms activated to remove heat from the body (e.g. cutaneous vasodilation) have the ability to move blood from the core to the skin. But this presents a competition for blood flow between the working muscle and the skin (22).

In addition to often competing in hot conditions, compared to athletes participating in other sports, elite tennis players are subjected to unique challenges. For example, matches are usually intense and of long duration punctuated by brief periods of intermittent rest (e.g. 90 s for court change-overs and 2 min between sets) and no substitutions are allowed. These factors when combined with match-play in hot environmental settings expose the elite tennis player to not only heat from the sun, but also to additional solar radiation reflected off of the tennis court (18). Matches usually occur in enclosed stadiums that limit the availability of convective heat removal as opposed to air movement available to a runner or cyclist (7, 30). The factors impose a high thermal strain on an elite tennis player and amplify the mental and physiological stress of competitive match play.

Because of the unique nature of the game, it is undetermined which type of cooling strategy may be most suitable for tennis athletes. Continuous cooling is surmised to be the most effective for blunting the rise in core temperature and assisting in performance (13, 14, 49); however this strategy may not be applicable to the tennis athlete as a wearable device may be uncomfortable, cumbersome and obtrusive which would possibly impede performance. Another solution may be intermittent ice applications to localized areas in an attempt to mitigate the effects of heat stress during 90-s court change-overs and the 2 min breaks between sets. It could also be surmised that a combined strategy of continuous cooling and intermittent ice pack applications may be the most optimal cooling strategy to lower core temperature and possibly enhance performance in elite tennis players.

The issue of increasing environmental temperatures and the heat stress of competition justifies research on the thermostasis of tennis athletes in order to ensure their health, safety and improved performance. Global temperatures continue to increase and future matches may be of longer duration and higher intensity as the quality of competition and fitness among elite players continues to improve. Because of the peculiar nature of the sport of tennis, optimal cooling strategies for mitigating the rise in core temperatures and enhancing performance may encompass intermittent localized ice-pack applications or a combined strategy of continuous personal cooling device plus intermittent localized cooling.

It is hypothesized that playing tennis in a hot environment increases core temperature and decreases performance and that cooling strategies that may mitigate the rise in core temperature of tennis players may increase performance.

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CHAPTER 2

IMPACT OF HEAT STRESS ON SHOT ACCURACY AND BODY TEMPERATURE IN ELITE TENNIS PLAYERS

ABSTRACT

The purpose of this study was to evaluate the effects of an acute bout of tennis-specific exhaustive exercise in a hot environment on shot accuracy and body temperature in elite tennis players. **Methods**: Nine male tennis athletes (age = 20 ± 3 years, height = 183.6 ± 6.6 cm, weight = 74.5 ± 12.5 kg) performed 2 counter-balanced trials which were randomly assigned consisting of high intensity exercise simulating the physiological demands of a tennis match in a temperate (TE) (22 °C, rH 31%) or hot (HOT) (37 °C, rH 38%) conditions. Rectal (T_{re}) and skin (T_{sk}) temperatures were recorded before and after the high intensity exercise bout. Following high intensity exercise, participants performed a 10-point shot accuracy (SA) test on an indoor tennis court where each shot was scored and recorded. **Results:** Following the HOT trial, T_{re} (38.5 ± 0.4 °C) and T_{sk} (35.0 ± 1.6 °C) were significantly higher compared to their measures following the temperate condition (37.8 ± 0.7 °C and 32.0 ± 1.3 °C, respectively). A large drop in shot accuracy ($p = 0.003$) was found between the temperate (57.5 ± 17.9 au out of possible 100) and hot (33.4 ± 4.0 au) conditions, with the greatest difference found in the players with highest shot accuracy scores. **Discussion:** Heat stress significantly increased core temperature and decreased shot accuracy after high intensity simulated tennis exercise.

KEY WORDS: thermoregulation, athletic performance, heat strai

INTRODUCTION

Athletic activity in hot environments presents an increased cardiovascular strain because of elevated blood flow directed to the skin as part of thermoregulation and the need to maintain adequate blood flow to working skeletal muscle (15). This increased cardiovascular strain, coupled with amplified perceptual strain associated with hyperthermia (35) challenges one's ability to perform optimally while also avoiding dangerously high body temperature (16). The added physiological strain results in a decrease in performance and an increased risk of thermal injury. Therefore, research addressing performance in hot environments is vital for optimal health and performance of athletes.

Heretofore most research studies have only been performed on endurance athletes such as runners and cyclists (4, 24). However, heat stress and performance is a concern for sports which involve a mixed contribution from anaerobic and aerobic energy systems. For instance, one such sport- tennis- is commonly played outdoors in the heat. Recent studies have shown that core temperature during an elite tennis match is elevated to levels, as high as 40 °C which increases the risk of exertional heat illness (24, 25, 26). Because of this, the International Tennis Federation (ITF) acknowledges dangers associated with the sport and the risk of exertional heat exhaustion (26). Furthermore, as quality and depth of competition continues to improve, the duration of typical matches will likely continue to extend. Extended match duration further increases energy demand, thermal strain, and the likelihood of greater cumulative physical and mental fatigue (18, 19). However, there are no scientific studies available determining the specific effects of heat exposure on tennis performance among elite tennis competitors.

The purpose of this study was to evaluate the effects of an acute bout of tennis-specific exhaustive exercise in a hot environment on core and skin temperatures and shot accuracy in competitive elite tennis players. It was hypothesized that an exercise bout simulating the rigors of competitive tennis play in a hot environment would significantly increase core and skin temperatures and negatively impact shot accuracy compared to the same exercise performed in the temperate environment.

METHODS

Experimental Approach to the Problem

Nine competitive tennis players underwent two testing trials that were randomly assigned and counter-balanced over two non-consecutive days. The two trials consisted of high intensity, intermittent exercise on a treadmill while being exposed to either temperate or hot conditions. The exercise session ceased once the participant reported a ratings of perceived exertion (RPE) of 17 which lasted approximately 30 min on average. Following the exercise bout, the subjects transitioned to a brief resting period in order to simulate a 120 s “between set” rest period, which occurred in the same environment as the exercise bout. Rectal and skin temperatures were recorded at 2 crucial time points (at the start of the protocol and at the end of the rest period). After the high intensity exercise protocol, the participants performed a simulated tennis set against a ball machine on an indoor court. Shot accuracy was determined by comparing each shot against an objective 10-point shot accuracy rating scale and recorded for analysis. Changes in skin and core temperature as well as shot accuracy were recorded within each condition and compared between each trial.

Subjects

Nine male competitive tennis players participated in this study (age = 20 ± 3 years, height = 183.6 ± 6.6 cm, weight = 74.5 ± 12.5 kg). Participants were recruited from the university’s tennis club. The volunteer participants consisted of national competitors who have competed in

Div 1 club play on a national level. The subjects were considered “elite” because they have been playing tennis for at least 10 years; play, practice, or compete daily; and train consistently in tennis specific activities. They have either received professional tennis-specific training or have resided and trained at tennis training centers which produced elite athletes.

The participants were apparently healthy, free from cardiopulmonary and metabolic diseases according to the pre-screening medical history questionnaire. The subjects were asked to refrain from alcohol and avoid strenuous exercise for at least 24 hours prior to data collection. The subjects were allowed to consume their “normal” diet but were asked to avoid food consumption for 1 hour prior to data collection. The experimental protocol was granted ethical approval by the University’s Institutional Review Board for research involving human subjects and each participant provided written informed consent.

High Intensity Exercise Protocol

The subjects were randomly assigned the counter-balanced treatment orders. Trials were performed over two non-consecutive days to and included high intensity exercise, intermittent exercise while being exposed to either a temperate (TE) or heat stress (HOT) condition. The two testing days were separated by 72 hours. Each high intensity intermittent exercise bout occurred on a motorized treadmill (Model SOLE 500, SOLE Treadmills Inc., Salt Lake City, UT 84111) inside of a portable climate chamber that was structurally assembled in an Indoor Tennis facility. Six modular wooden components were used to construct a frame with dimensions of 3.86 m in length, 1.91 m in width, and 2.39 m in height. The frame was covered with extra heavy duty contractor grade 6 mil plastic sheeting (Contractor’s Choice, York, PA 17403). Three 1500 watt ceramic air heaters (Stanley Model 675900, Lasko Corp., Philadelphia, PA) were placed inside of the portable chamber and used during the hot trial. During each trial, the participants wore summer tennis apparel consisting of a shorts, a cotton t-shirt, and shoes specific to tennis (e.g. with a non-marking sole etc.).

The high intensity intermittent exercise protocol was adapted from Fabre et. al. (13), which was developed to emulate a tennis match in the form of a series of simulated rallies. A simulated rally consisted of the following in order: 15 - 30 seconds of treadmill running at a set speed that began at 6.5 kilometers per hour (kmph) and increased by 1.6 kmph during the following rallies until 16.1 kmph was reached; the subject then dismounted the treadmill and performed 2 simulated forehand and 2 simulated backhand strokes proceeded by a 20 second recovery period in the "set position". One series was considered a full completion of 6 rallies which was considered a simulated tennis game. The first three series were repeated consecutively. Following the third series, a 90 s rest period was allowed to simulate a "court changeover". Afterwards, the 90 second rest period was performed every time a subsequent pair of series was completed. The subjects held a tennis racquet in their dominant hand throughout the exercise protocol. Because match intensity is often regulated on perceived effort (Gomes et al., 2011), termination of the tennis-simulated exercise protocol was dictated with the use of RPE using a Borg's 6-20 scale. The highest previously reported RPE values obtained in elite tennis players during individual-play was 17 (23). Therefore, the simulated exercise protocol was stopped when the subjects reported an RPE of 17. Following the exhaustive exercise trial, a 2-minute rest period was allowed to simulate a "between set rest period".

Body temperature measures

T_c was indexed by rectal temperature (T_{re}) using a copper-constantan thermocouple (Model RET-1, PhysiTemp© Instruments, Inc., Clifton, NJ 07013). Participants inserted the thermocouple approximately 8-10 cm past the anal sphincter. T_{sk} (Model Thermaskin CBL, PhysiTemp© Instruments, Inc., Clifton, NJ 07013) of a single site was measured approximately 10-15 cm measuring inferior to the top of the participant's right shoulder directly down the back, affixed over the participant's right shoulder blade. Temperature measures were recorded at the start of the high intensity exercise protocols (T_{re}StartTE, T_{re}StartHOT, T_{sk}StartTE, T_{sk}StartHOT) and following the 2 minutes of seated cool-down (T_{re}EndTE, T_{re}EndHOT, T_{sk}EndTE, T_{sk}EndHOT). The following abbreviations were applied to represent each condition:

Core temperature metrics

- The starting core temperature of the temperate condition = T_{re} StartTE
- The ending core temperature of the temperate condition = T_{re}EndTE
- The starting core temperature of the hot condition = T_{re}StartHOT
- The ending core temperature of the hot condition = T_{re}EndHOT

Skin temperature metrics

- The starting skin temperature of the temperate condition = T_{sk}StartTE
- The ending skin temperature of the temperate condition = T_{sk}EndTE
- The starting skin temperature of the hot condition = T_{sk}StartHOT
- The ending skin temperature of the hot condition = T_{sk}EndHOT

Shot Accuracy Test

Following the 2-minute rest period that followed the high intensity exercise bout, subjects went directly to the indoor tennis court which was immediately adjacent to the portable heat chamber. The subjects performed a 10-shot tennis-play bout against a tennis ball machine (Playmate Volley, Playmate™, Morrisville, NC 27560). The ball machine was set and programmed into its most aggressive "attack" mode simulating play with an opposing elite player. New tennis balls (Head Penn©, Jeanette, PA 16644) were used for each set of trials. The ball machine was capable of consistent targeted accuracy, randomized oscillation, and ball speeds up to 129 kmph. The ball machine was placed with the front directly over the center mark on the baseline on the opposite side of the court from the player. A randomized series of 10 shots occurred toward the participant, simulating play against an elite opponent.

Each participant's shot accuracy was subjectively measured with a 10-point grading scale where "0" represented a shot into the net or out-of-bounds, a "5" represented a mid-court returnable ball, and a "10" represented an unreturnable ball (Figure 2.1). The scale was designed by the author, a certified tennis professional (i.e. Professional Tennis Registry member #51592), with many years of tennis play, professional teaching and coaching. Three certified professional tennis instructors reviewed the scale for validation. A single technician who was blind to the study used the scale to record shot accuracy of the trials. The total of the 10 graded shots was recorded as shot accuracy with a maximum score of 100.

Statistical Analysis

Statistical procedures were performed with Statistical Package for the Social Sciences (version 22.0 IBM© SPSS© Statistics, Chicago, IL). A 2 x 2 (treatment, temperate vs hot x time, baseline vs. end) repeated measures analysis of variance (ANOVA) was used to evaluate temperature outcome variables. In the event of a significant omnibus ANOVA, a paired sample t-test was performed using a Bonferroni adjusted α level. Paired samples t-tests were used to determine the mean differences in shot accuracy between TE and HOT trials. Effect sizes were expressed as Cohen's *d* statistic (17). Hopkin's scale for determining the magnitude of the effect size was used where 0-0.2 = trivial, 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, >2.0 = very large (17). The differences (i.e., difference = TE – HOT) between the TE and HOT trials were also reported for each of the time points. Pearson product correlations were performed to determine if the differences in shot accuracy were related to the differences in T_{re} and T_{sk}. The magnitude of the correlation coefficient was qualified by the Hopkins et al. (17) method where an r of 0 to 0.30 was considered small, 0.31 to 0.49 was moderate, 0.50 to 0.69 was large, 0.70 to 0.89 was very large, and 0.90 to 1.00 was near perfect. Furthermore, regression procedures were performed to determine the extent of variation in the difference in shot accuracy that could be accounted for by the differences in the temperature metrics. Bivariate outliers were determined as a standardized residual score of equal to or greater than 2.0. An α level of 0.05 was used for all hypothesis test.

RESULTS

Total exercise time until the targeted RPE of 17 was achieved was 31.9 ± 12.8 minutes for the TE trial and 27.5 ± 10.4 minutes for the HOT trial ($p < 0.01$). Despite exercising ~5 min longer in the temperate condition, subjects performed worse in HOT and had higher $T_{re.}$

Temperature Comparisons

Individual and mean data for the temperature measures are presented in Table 1. For the T_{re} variables, T_{re}EndHOT was higher than both T_{re}StartHOT ($p < 0.001$, Cohen's d = 3.79) and T_{re}EndT ($p < 0.001$, Cohen's d = 1.22). There was no difference between T_{re}StartTE and T_{re}EndTE ($p = 0.082$, Cohen's d = 0.98) nor between T_{re}StartTE and T_{re}StartHOT ($p = 0.28$, Cohen's d = 0.27).

For the T_{sk} variables, TskEndTE was higher than TskStartTE ($p = 0.001$, Cohen's d = 1.21). However, the difference between T_{sk}StartHOT and T_{sk}EndHOT was *moderate* (Cohen's d = 1.06) and not significant ($p = 0.03$) according to the Bonferonni adjusted α level. Starting T_{sk} was significantly higher in the HOT compared to the TE condition ($p = 0.01$, Cohen's d = 1.47).

Ending T_{sk} was also significantly higher in the HOT compared to the TE condition ($p = 0.012$, Cohen's $d = 1.23$).

Shot Accuracy

Individual and mean values for shot accuracy between the two conditions are reported in Table 2. A significantly better shot accuracy was found with a large effect size for the TE compared to the HOT condition. A range of individual differences are reported in Table 2, with the higher scoring subjects following the TE condition showing a greater decrease in performance following the HOT trial. The correlation between shot accuracy following the TE condition and the difference in shot accuracy was *near perfect* ($r = 0.98$, $p < 0.001$, Figure 2.2).

Correlations of the Differences in the Studied Variables

Figure 3 represents the scatterplot of the relationship between the difference in shot accuracy and the difference in T_{re}. A *moderate* and non-significant correlation was found ($r = -0.48$, $p = 0.19$) between the two variables. However, one subject showed a standardized residual score of 2.1, suggesting this data point was an outlier to this bivariate comparison. When removed, the correlation coefficient increased to *near perfect* and significant ($r = -0.94$, $p = 0.001$). Figure 4 represents the scatterplot of the relationship between the difference in shot accuracy and the difference in T_{sk}. This correlation showed to be *weak* and non-significant ($r = -0.17$, $p = 0.655$), with no outliers present.

DISCUSSION

The purpose of this study was to evaluate the effects of an acute bout of tennis-specific high intensity exercise in a hot environment (i.e. heat stress) on core and skin temperatures and shot accuracy in competitive elite tennis players. The hypothesis that the exercise bout in the hot environment would increase core and skin temperatures and decrease shot accuracy was accepted. T_{re} of the HOT trial significantly increased from the start to the end of the bout. However, T_{re} did not significantly increase from start to end in the TE condition. Furthermore, the end T_{re} following the HOT trial was higher than the end T_{re} of the TE trial. Therefore, it appeared that the high intensity exercise bout influenced core temperature only under the HOT condition. Skin temperature increased from the baseline to the end of the exercise in both conditions. However, the difference was statistically significant only in the TE condition. Skin temperature was consistently and significantly higher in the HOT compared to the TE condition when comparing both time points. In terms of shot accuracy, a significantly better score was performed after the TE exercise bout than shot accuracy performed after the HOT exercise bout. Concerning the relationships of the difference in shot accuracy and difference in the temperature metrics between the two conditions, no significant relationships were found. However, after the removal of one subject lying outside the normal range of data between the relationship of the difference core temperature and the difference in shot accuracy, the correlation of this relationship indicated to be *near perfect* and significant.

These findings support previous studies indicating that heat stress with exercise negatively impacts performance and challenges thermoregulation (16, 2, 3, 7, 25). However, most of the previous research has primarily focused on endurance athletes engaged in steady state activities, such as running and cycling (2, 20, 9). This is the first study to examine the effects of heat strain among elite tennis players.

The intermittent periods of high intensity exertion followed by very brief periods of recovery during tennis-play provides a strain to the cardiovascular and thermoregulatory systems (4, 16). In addition, sun exposure and reflective solar energy from the court surface provides a heat stress that can further contribute to the accumulating physiological strain (4). Homeostatic core temperature is typically maintained between a very narrow limits of 36.1 - 38.8 °C (28). High core temperatures dramatically increase the risk of heat-related injuries (6, 26). In the TE condition, the high intensity exercise bout did not increase $T_{re.}$ However, the additive effects of being physically active in a hot environment resulted in a net heat gain (28), which increased T_c during the HOT trial. Furthermore, the significant increase in T_c in the HOT condition occurred in approximately half an hour, on average. This is an important consideration since a player may be exposed to environmental heat for a longer time period during a typical tennis match (13). A longer bout of exercise in the heat may have provided a greater increase in T_{re}. At any rate, practitioners need to be aware that tennis-specific activity in a hot environment increases T_c and may also increase the risk of a thermal injury.

Skin temperature was significantly higher at both time points (i.e., “start” and “end”) when the exercise was performed in the HOT compared to the TE condition. When exposed to heat, blood is shunted from the core to the skin for the removal of heat to the external environment (28). This process occurs within minutes of being exposed to a hot temperature (28), which likely explains why T_{sk} in the HOT trial was significantly higher than T_{sk} in the TE trial, even at the start of the bout.

An accurate tennis shot involves the integrative mix of many intricate physiological, psychological, and biomechanical responses. Therefore, it is likely that the findings of compromised shot accuracy following heat stress could be explained by a number of possibilities. For instance, sweating is increased upon physical exertion in hot environments (28), such as the heat stress condition employed in the study. The palm of the hand is a major site for heat loss (28, 30). Sweating of the palms may influence a player’s traditional grip and hence change the angle of the racket when the ball makes contact. Furthermore, heat exposure has been shown to decrease speed (11), delay reaction time (8,9,18), slow anticipatory responses (7), and lower repeatability of anaerobic performance (16). In addition, intense exercise in a hot environment negatively affected decisional and perceptual tasks (8). Any number of the aforementioned factors may compromise an athlete's ability to re-position for subsequent shots resulting in a failure to maintain optimal physical performance. This is important because the fast pace nature of the game and high ball speed at the elite level make even the slightest mistake in repositioning between shots a detrimental factor to an athlete's ability to execute accurately.

In fact, the findings further suggest the more elite players experienced the greatest drop in shot accuracy after exposure to heat. This is presented in Table 1 as Subjects 1, 2, 3, 4, 7, and 9 displayed a higher shot accuracy score in the temperate environment yet the greatest decline following exposure to heat stress. In contrast, the lower performing players (e.g., Subjects 5, 6, and 8 – Table 1) had very small differences in shot accuracy between the two trials, suggesting that heat stress may not have had as great of an impact on players with lessor shot accuracy capability. In addition, the results showed a *near perfect* correlation between shot accuracy performance following T and the difference in shot accuracy performance between the two trials. Therefore, while the mean difference suggests that shot accuracy decreases on average following heat stress, the higher level athletes experienced the greatest drop in performance. This is most likely due to the possibility that even minute external challenges may dramatically impact the intricate and integrative nature of an elite tennis shot.

The results suggest that heat exposure influences both shot accuracy and T_{re} because the differences of both parameters between the two trials were significantly and *near perfectly* related. However, this relationship was revealed after controlling for one outlier within the bivariate comparison. The reason for the outlier cannot be fully explained. However, additional factors may influence shot accuracy other than physiological challenges, such as perception of effort (14). Nevertheless, the strong association between changes in T_{re} and changes in performance on the elite tennis player emphasizes the need for future research specifically addressing tennis-related exertion in hot environments for optimal health and performance.

There are some limitations of the study that must be highlighted. First, the study involved a fairly low sample size. However, the sample of 9 subjects is a higher number than a standard elite male tennis team which consists typically of only 6 athletes. Second, the findings of the study may be explained by differences in hydration status between the hot and temperate conditions. Unfortunately, hydration status was not evaluated. However, hydration was moderately controlled as water ingestion was kept consistent between both trials. Third, the exhaustive exercise bout occurred on a treadmill rather than a tennis court. This may bring into question the ecological validity of the study. However, the high intensity exercise bout was designed to simulate the physiological responses of tennis-play and has been used in previous research on tennis players (13). Furthermore, this simulated stimulus was convenient and practical for use in the heat chamber.

PRACTICAL APPLICATIONS

The results presented in this study may assist practitioners in managing tennis players' abilities to achieve optimal shot accuracy following exposure to a hot environment. The study found that heat exposure decreased shot accuracy and the drop was more substantial in the higher performing players. Exposure to heat stress significantly increased core body temperature. Therefore, coaches who work with elite tennis players may need to adopt and ensure heat acclimation policies and procedures before an athlete plays in a hot environment. Furthermore, the study found that the changes in core temperature and the decline in performance were related.

More research is needed to specifically address heat stress and body temperature changes in elite tennis players in order to optimize performance and minimize risks of heat related illnesses.

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Table 2.1. Participant rectal and skin temperatures for temperate and hot conditions.

	T_{re}				T_{sk}			
	TE		Hot		TE		Hot	
Subjects	T_{re}Start	T_{re}End	T_{re}Start	T_{re}End	T_{sk}Start	T_{sk}End	T_{sk}Start	T_{sk}End
1	37.1	38.1	37.3	38.9	30.3	31.7	33.6	37.5
2	37.8	36.4	37.4	38.1	30.3	31.4	33.0	34.4
3	37.0	37.6	37.4	38.2	31.1	33.0	35.0	33.9
4	37.3	37.3	37.5	38.2	31.2	33.2	33.0	33.5
5	37.6	38.0	37.2	38.5	33.2	34.4	35.2	36.0
6	37.3	38.0	37.4	38.4	32.1	34.3	31.3	34.4
7	36.9	38.7	37.2	38.8	33.0	35.3	34.1	37.5
8	37.3	38.7	37.4	39.0	28.8	32.3	33.0	34.1
9	36.2	37.2	37.0	38.1	33.3	33.0	33.4	33.8
Mean	**37.2**	**37.8**	**37.3**	**38.5*†**	**31.5**	**33.2***	**33.5†**	**35.0†**
SD	**0.5**	**0.7**	**0.2**	**0.4**	**1.5**	**1.3**	**1.2**	**1.6**

TE= Temperate condition, Hot = hot condition, T_{re} = rectal temperature, T_{sk} = skin temperature, T_{re}StartT = T_{re} at the start of the TE condition, T_{re}EndTE = T_{re} at the end of the TE condition, T_{re}StartHot = T_{re} at the start of the Hot condition, T_{re}EndHot = T_{re} at the end of the Hot condition, T_{sk}StartTE = T_{sk} at the start of the TE condition, T_{sk}EndTE = T_{sk} at the end of the TE condition, T_{sk}StartHot = T_{sk} at the start of the Hot condition, T_{sk}EndHot = T_{sk} at the end of the Hot condition, SD = standard deviation.

*The end temperature was significantly higher than start ($p < 0.012$)

†Significantly higher in the Hot compared to TE of the same time point ($p < 0.012$)

Table 2.2. Individual and group mean values for shot accuracy.

	Shot Accuracy		
Subjects	**TE**	**Hot**	**Diff**
1	61.0	40.0	21.0
2	86.5	37.0	49.5
3	58.0	36.0	22.0
4	62.0	33.0	29.0
5	40.0	36.0	4.0
6	35.0	31.0	4.0
7	77.0	30.0	47.0
8	36.0	29.0	7.0
9	62.0	29.0	33.0
Mean	**57.5**	**33.4**	
SD	**17.9**	**4.0**	
p	**0.003**		
ES	**1.86**		

TE = Temperate, SA = shot accuracy, SD = standard deviation, ES = effect size.

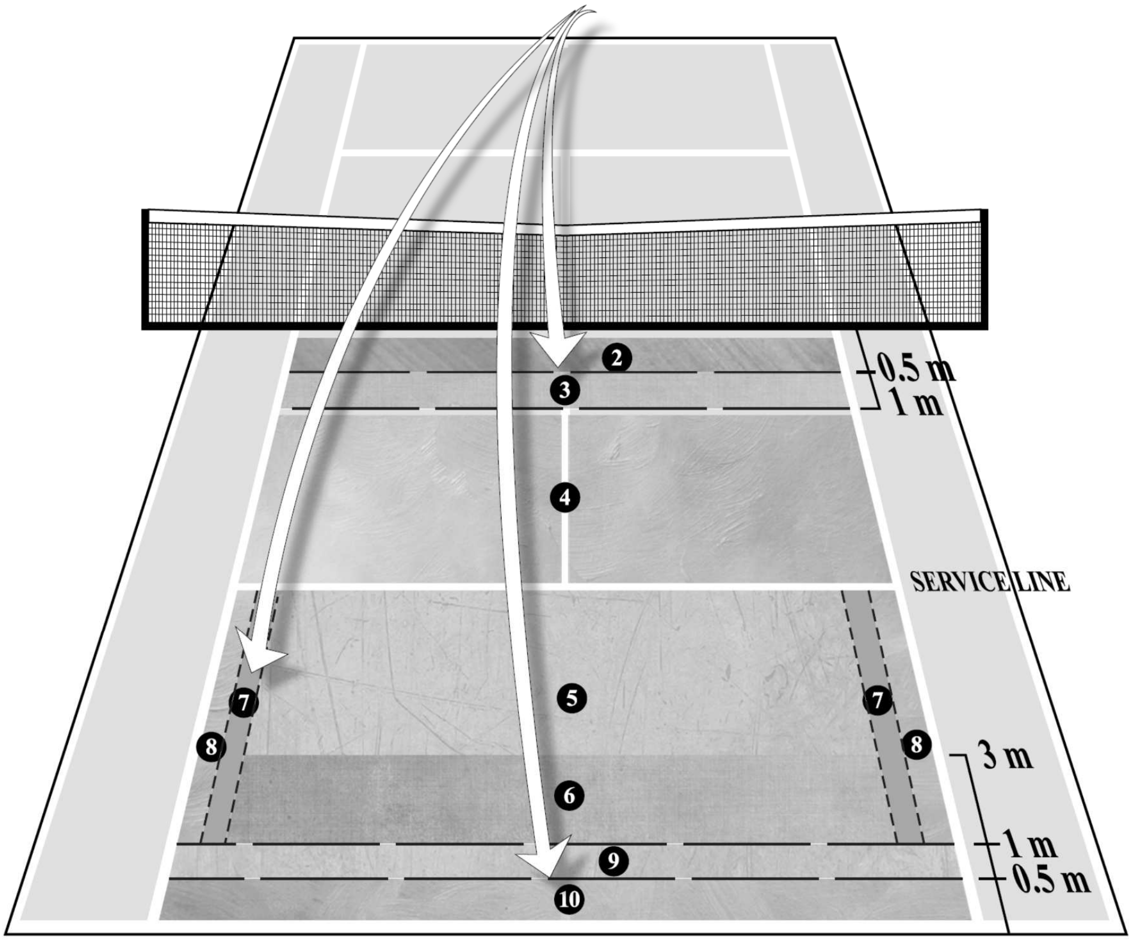

Figure 2.1.Schematic diagram of shot accuracy scoring scale.
Each shot was based on the following:

0 = No successful return. (E.g. ball into the net or out of bounds)
2 = Ball landing 0.5m from the net on and within the singles sideline
3 = Ball landing 1m from the net on and within the singles sideline
4 = Ball landing between the service line & w/in 1m of net and on & w/in singles sideline
5 = Ball landing over 3m inside baseline & b/tw service line on & w/in singles sideline
6 = Ball landing over 1m inside baseline & w/in the 3m of it on & w/in singles sideline
7 = Ball landing on or within 1m inside of the singles side line
8 = Ball landing on or within .5 m inside the singles side line
9 = Ball landing on or within 1m inside of the baseline
10 = Ball landing on or within 0.5 m on or inside the baseline and b/w the singles sideline

The total score of 10 shots was calculated, where the highest possible score was 100 and the lowest possible score was 0.

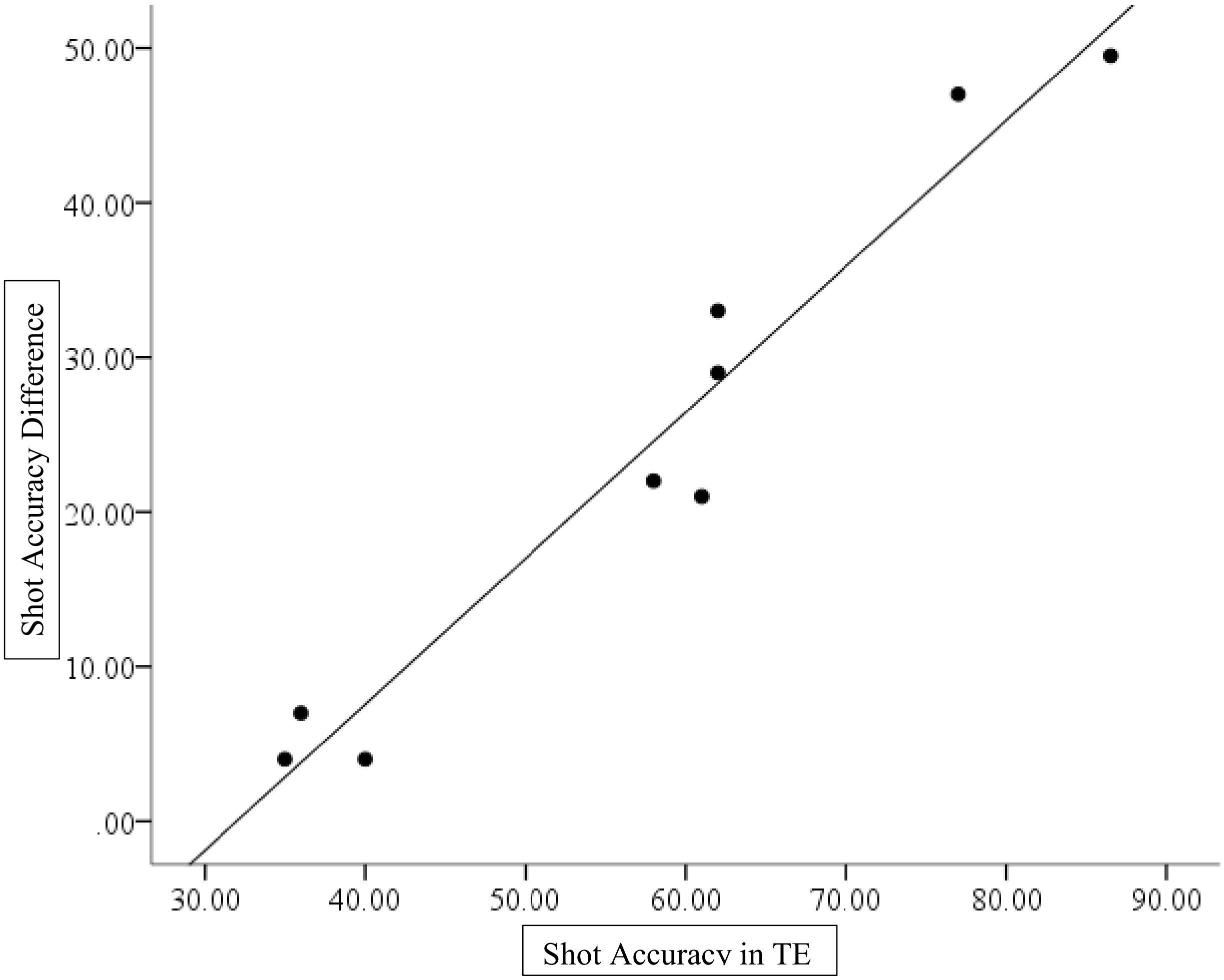

Figure 2.2. Scatterplot of the difference in shot accuracy of the temperate and hot trials. (SA differences = shot accuracy following TE – shot accuracy following HOT) and shot accuracy following the TE. TE = temperate condition, SA = shot accuracy

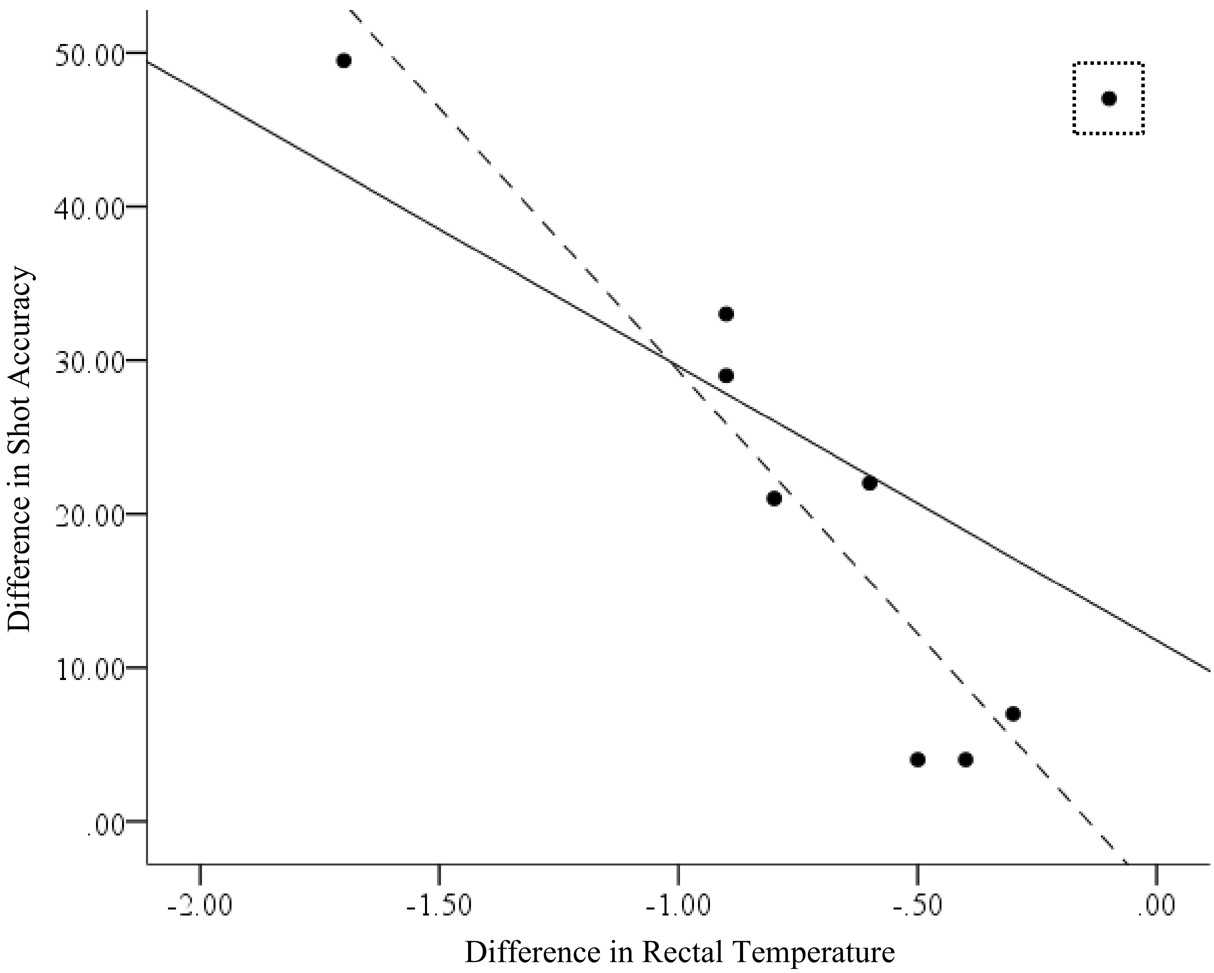

Figure 2.3. Scatterplot of relationship between of differences in shot accuracy and core temperature. The difference in both variables was calculated as follows: difference = temperate – hot condition. The dotted box is placed to highlight an outlier. The solid line represents the trend line of the relationship all subjects included (n = 9, r = -0.48, p = 0.19). The dashed line represents the trend line of the relationship when the outlier was removed (n = 8, r = -0.94, p = 0.001).

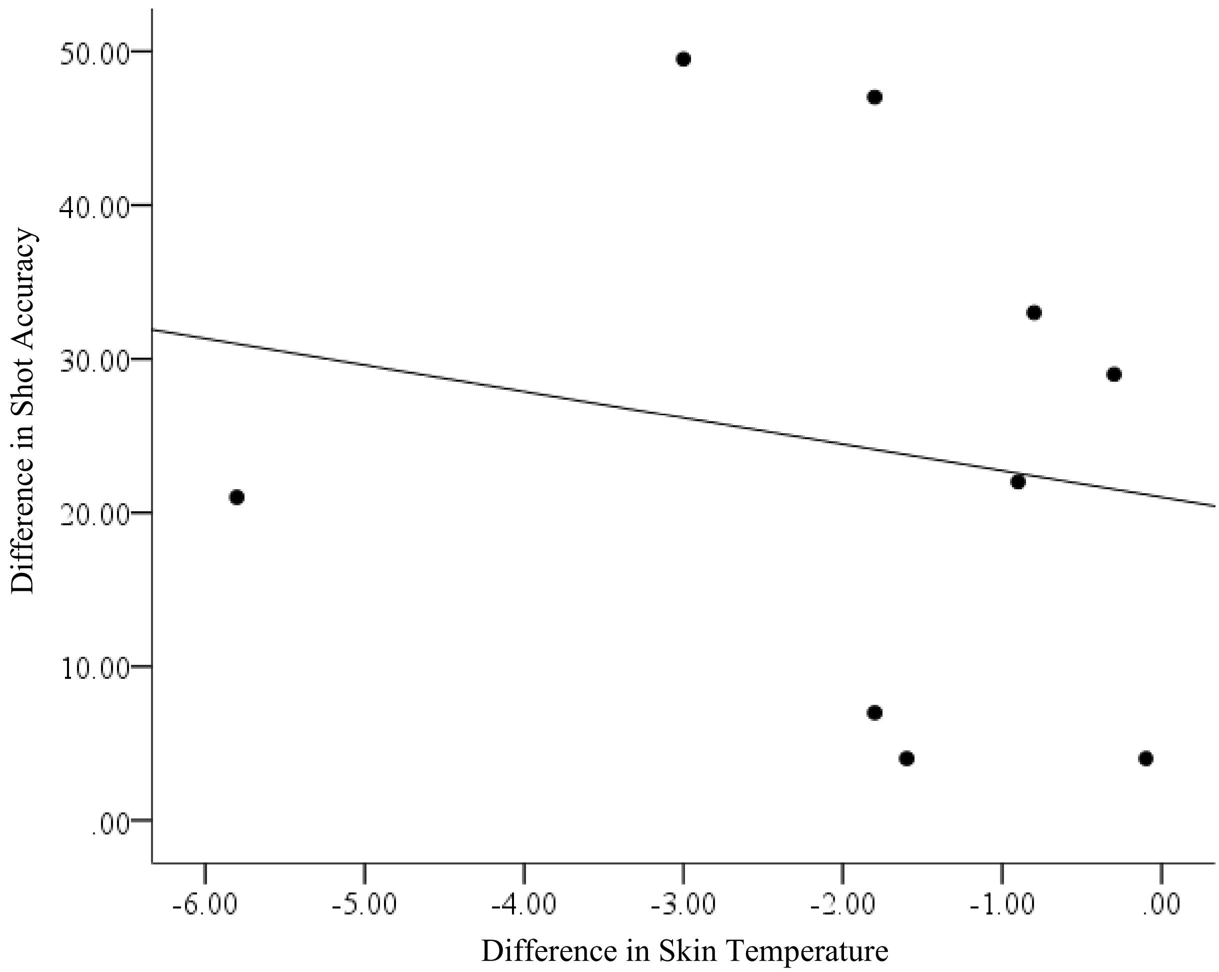

Figure 2.4. Scatterplot of relationship of differences of shot accuracy and skin temperature. The difference in both variables was calculated as follows: difference = temperate – hot condition.

CHAPTER 3

EFFECTS OF INTERMITTENT COOLING ON HEAT STRAIN AND SHOT ACCURACY IN ELITE TENNIS PLAYERS

ABSTRACT

The purpose of this study was to investigate the effects of intermittent periods of localized cooling on core body temperature and performance in elite tennis athletes exposed to exhaustive exercise in a hot environment. **Methods**: Nine male tennis athletes (age = 20 ± 3 years, height = 183.6 ± 6.6 cm, weight = 74.5 ± 12.5 kg) performed counter-balanced trials of high intensity exercise simulating the physiological demands of tennis in a hot environment (37 °C, 38% rH) with ice intermittently applied to the abdominal walls and thighs (ICE) and without the ice applications (CONTROL). Rectal (T_{re}) and skin (T_{sk}) temperatures were recorded before and after the exhaustive exercise bout. Following high intensity exercise, the participants had a 2 min rest period. T_{re} and T_{sk} were also recorded at the end of the rest period. After the rest period subjects performed a 10-point shot accuracy test on an indoor tennis court where each shot was scored and recorded. **Results:** T_{re} values were not different between baseline and at the end of the exercise protocol and the end of the rest period in either treatment condition. Likewise, T_{re} was not different between treatments at either time point. Shot accuracy score was 33.4 ± 4.0 (arbitrary units) following the HOT trial and 47.2 ± 12.7 following the ICE trial, which was significantly different ($p < 0.05$, Cohen's d = 1.47). **Discussion:** The cooling treatment improved shot accuracy, without a significant impact on T_{re}. The mechanism(s) explaining this finding is uncertain, but may be attributable to perceptual factors.

KEY WORDS: athletic performance, heat stress, cooling interventions

INTRODUCTION

Elite tennis matches are most often played in hot and humid environmental settings, which uniquely challenge the thermoregulatory capacity of tennis athletes compared to other sports. For instances matches are usually intense and of long duration with only very small incremental rest periods in a game where there are no substitutions. Additionally, there is little to no ambient wind available for convective heat removal as there is with running or cycling. The tennis player is therefore subjected to not only an increased level of environmental temperature from solar radiation from the sun, but also from heat eradiating from the tennis court and the sun's ray reflecting off of the court's surface. This environmental condition presents an amplified dual challenge for the redistribution of blood flow to support active skeletal muscle during tennis play and initiation of the sweat response at the skin for evaporation of heat for thermoregulation (24). This combined requirements of active skeletal muscle metabolism for exercise and thermoregulation creates an internal competition for a substantial percentage of cardiac output (43**).** For the elite tennis athlete, this could result in decreased performance and increase the risk of heat illness (27). Therefore, strategies that enhance performance in these environments and mitigate the consequence of heat stress are necessary.

Traditionally, cooling interventions to reduce thermal strain have been used mainly for occupational performance in extreme environments, such as military personnel and fire fighters (26). However, more recent research indicates that cooling interventions may serve as aids in athletes who experience hyperthermia by lowering core temperature (21). Additional athletic research indicates that cooling interventions have resulted in improved performance and reduced thermal strain in runners and cyclists (26, 52). Cooling strategies have also been shown to enhance performance (53) and promote lower thermal strain (28) in soccer players performing in hot environments.

Tennis is a sport that is also subjected to the consequences of performance in hot and humid environments. However, there is limited research determining the effects of cooling strategies on tennis performance. This is concerning, as there are a number of differences between tennis and the other sports that have been the focal points within this area of study. For instance, tennis is a sport that involves a mixed contribution of anaerobic and aerobic energy sources (34). This continual shift in metabolic response during increased intensity when played in a hot and humid environment is an additional challenge to homeostatic control that may also interfere with thermoregulation, and the onset of fatigue that can affect performance (20, 45).

There are no substitutions in tennis play. Therefore, the tennis player is subjected to a longer duration of play in hot and humid environments making them more susceptible to heat stress (39). Furthermore, unlike sports such as soccer, there are no intermissions during tennis play. A lack of an extended break-period provides an added inconvenience for the application of a cooling technique. In addition, dissimilar to runners and cyclists, tennis players do not have the constant, convective source of continuous ambient wind (42).

Cooling studies which have examined cold-water immersion for extended periods of time have indicated improved performance between 2 bouts of exercise in the heat (52). Improved performance between 2 bouts of cycling has also been observed with an intervention of cold-water immersion in a hot environment (51); however these findings are difficult to generalize and impractically applicable to the sport of tennis. Therefore, the purpose of this study was to investigate the effects of brief intermittent periods of localized cooling on core body temperature and performance in elite tennis athletes when exposed to exhaustive exercise in a hot environment. It is hypothesized that brief intermittent localized cooling on core body temperature may mitigate the rise in core temperature and increase performance.

METHODS

Experimental Approach to the Problem

Nine elite tennis players underwent two testing trials separated by 48 h and performed in counter-balanced order. Each trial consisted of high intensity, intermittent tennis-simulation exercise on a treadmill in a hot environment, with one involving a cooling device applied to the following areas: anterior and posterior portions of the abdominal wall; and medial and lateral portions of the thigh intermittently during a 90 s simulated court change over and a 2 min rest period. Core and skin temperatures were measured at baseline and after both exercise trials. After a brief 2 min rest period, the participants performed a simulated tennis set against a ball machine on an indoor court. Shot accuracy was determined with an objective 10-point shot accuracy rating scale. The recorded changes in skin and core temperature, as well as shot accuracy, were compared between each trial.

Subjects

Nine male competitive elite tennis players volunteered to participate in this study (age = 20 ± 3 years, height = 183.6 ± 6.6 cm, weight = 74.5 ± 12.5 kg). Participants were recruited from the university's tennis club. The participants consisted of national competitors who have competed in Division I club play. The athletic subjects were considered "elite" because they have been involved extensively in the sport of tennis. They had played tennis for at least 10 years, played, practiced, or competed daily, as well as train consistently in tennis specific activities. All of the participants had received professional tennis-specific training. Some of the athletes had also resided and trained at elite tennis training centers.

The participants were healthy, free from cardiopulmonary and metabolic diseases according to the pre-screening stratification processes and medical history questionnaire. The subjects were asked to abstain from alcohol and avoid strenuous exercise for at least 24 hours prior to exercise trials. Subjects were allowed to consume a “normal” diet, but were asked to avoid food consumption for at least 60 minutes prior to data collection. The experimental protocol was approved by the University’s Institutional Review Board for research involving human subjects. Each participant had all of the procedures explained and all questions answered before beginning any procedures, and each participant provided and signed a written informed consent form before participating.

Exhaustive Exercise Protocol

The subjects participated in two trials of high intensity, intermittent exercise in counter-balanced order. Exercise in each trial was performed in a hot environment (37 °C, 385 rH), but one trial included intermittent cooling (ICE) while the other did not (CONTROL). Each high intensity exercise bout occurred on a motorized treadmill (Model SOLE 500, SOLE Treadmills Inc., Salt Lake City, UT 84111) in a portable climate chamber that was assembled in an Indoor Tennis facility. Six modular wooden components were used to construct a frame with dimensions of 3.86 m in length, 1.91 m in width, and 2.39 m in height. The frame was enclosed with extra heavy duty contractor grade 6 mil plastic sheeting (Contractor’s Choice, York, PA 17403). Three 1500 watt ceramic air heaters (Stanley Model 675900, Lasko Corp., Philadelphia, PA) were placed inside of the portable chamber and used during the two trials. During each trial, the participants wore summer tennis apparel consisting of shorts, a cotton t-shirt, and official "tennis" shoes with non-marking outsoles.

The high intensity exercise protocol was adapted from Fabre et. al. (19), which was developed to imitate a tennis match in the form of a series of simulated rallies. See Fabre et.al. (19) for detailed information. A simulated rally consisted of the following in order: 15 - 30 s of treadmill running at a set speed that began at 6.4 kmph and increased by 1.61 kmph during the following rallies until 16.1 kmph was reached; 2 simulated forehand and 2 simulated backhand strokes; 20 second recovery period in the "set position". One series was considered a full completion of 6 rallies which simulated a tennis game. The first three series were repeated consecutively. Following the third series, a 90 s rest period was allowed to simulate "court changeover". Afterwards, the 90 s rest period was performed every time a subsequent pair of series was completed. The subjects held a tennis racquet in their dominant hand throughout the exercise protocol. Because match intensity is often regulated on perceived effort (22) termination of the tennis-simulated exercise protocol was dictated with the use of RPE using a Borg's 6-20 scale. The highest previously reported RPE values obtained in elite tennis players during individual-play was 17 (37). Therefore, the simulated exercise protocol was stopped when the subjects reported an RPE of 17. Following the high intensity exercise trial, a 2-minute rest period was allowed to replicate a "between set" rest period.

Body Temperature Measures

T_c was indexed by rectal temperature (T_{re}) using a copper-constantan thermocouple (Model RET-1, PhysiTemp© Instruments, Inc., Clifton, NJ 07013). Participants inserted the thermocouple approximately 8-10 cm past the anal sphincter. T_{sk} (Model Thermaskin CBL, PhysiTemp© Instruments, Inc., Clifton, NJ 07013) of a single site was measured approximately

10-15 cm measuring inferior to the top of the participant's right shoulder directly down the back, affixed over the participant's right shoulder blade. Both T_{re} and T_{sk} were connected to and monitored by a portable battery operated temperature monitor (ThermAlert Model TH-8, PhysiTemp © Instruments Inc., Clifton, NJ 07013). The temperature metrics were recorded at the start of the high intensity exercise protocols (T_{re}StartICE, T_{re}StartCONTROL, T_{sk}StartICE, T_{re}StartCONTROL), at the end of the exercise protocol and following the 2 minutes of seated cool-down of the resting phase (T_{re} ExEndICE, T_{re}RestEndICE; T_{re} ExEndCONTROL, T_{re}RestEndCONTROL; T_{sk}ExEndICE, T_{sk} RestEndICE; T_{sk}ExEndCONTROL, T_{sk}RestEndCONTROL).

The following abbreviations were applied to represent each condition:

Core temperature Metrics of each Condition:

Treatment (ICE)

- Starting core temperature = T_{re} StartICE
- Ending core temperature of Exercise Phase = T_{re}ExEndICE
- Ending core temperature of Resting Phase = T_{re}RestEndICE

CONTROL

- Starting core temperature = T_{re}StartCONTROL
- Ending core temperature of Exercise Phase = T_{re}ExEndCONTROL
- Ending core temperature of Resting Phase = T_{re} RestEndCONTROL

Skin temperature metrics of each condition:

Treatment (ICE)

- Starting skin temperature = T_{sk}StartICE
- Ending skin temperature of Exercise Phase = T_{sk}ExEndICE

- Ending skin temperature of Resting Phase = T_{sk} RestEndICE

CONTROL

- Starting skin temperature = T_{sk}StartCONTROL
- Ending skin temperature of Exercise Phase = T_{sk}ExEndCONTROL
- Ending skin temperature of Resting Phase = T_{sk} RestEndCONTROL

Shot Accuracy Test

Following the 2-minute rest period that followed the exhaustive exercise bout, subjects went directly to the indoor tennis court immediately beside the heat chamber. The subjects performed a 10-point tennis-play bout against a tennis ball machine (Playmate Volley, Playmate™, Morrisville, NC 27560). The ball machine was set and programmed into an aggressive "attack" mode imitating play with an opposing elite player. New tennis balls (Head Penn©, Jeanette, PA 16644) were used for each set of trials. The ball machine was capable of consistent targeted accuracy, randomized oscillation, and ball speeds up to 129 kmph. The ball machine was positioned in place with the front directly over the center mark on the baseline on the opposite side of the court from the player. A series of 10 randomized shots were sent toward the participant, replicating play against an elite opponent. The participant stood behind the baseline directly behind the center mark at the start of the shot sequence.

Each participant's shot accuracy was measured with a 10-point grading scale where "0" represented a shot out-of-bounds or into the net, a "5" represented a mid-court returnable ball, a "10" represented an unreturnable ball landing in the very back portion of the court (Figure 3.1). The scale was designed by the author, a certified tennis professional (i.e. Professional Tennis Registry member #51592), with several decades in tennis play, professional teaching and coaching. Three certified professional tennis instructors reviewed the scale for validation. The shot accuracy score was recorded by a single technician blind to the study. Ten graded shots were totaled and documented as the variable of shot accuracy.

Statistical Analysis

Statistical procedures were administered with Statistical Package for the Social Sciences (V 22.0 IBM© SPSS© Statistics, Chicago, IL). A 3 x 2 design repeated measures ANOVA procedure was to evaluate the difference in both temperature measures across the 3 time points of the high intensity exercise protocol (baseline, ExEnd, RestEnd) and each treatment condition (CONTROL vs ICE). In the event of a significant omnibus test, a paired samples t-test with a Bonferroni adjusted α level was performed to determine individual differences. Paired samples t-tests were used to determine the mean differences in shot accuracy between CONTROL and ICE trials. Cohen's *d* statistic was used to reflect the effect size of the differences in the studied variables (29). Hopkin's scale for determining the magnitude of the effect size was used where 0-0.2 = trivial, 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, >2.0 = very large (29). An alpha level of 0.05 was used for all hypothesis tests.

RESULTS

Total exercise time of the exhaustive exercise protocol (i.e., when the subjects reached an RPE of 17) was 27.5 ± 10.4 for the CONTROL trial and 31.7 ± 7.0 min for the ICE trial, which was not significantly different ($p = 0.394$, Cohen's d = 0.47). Mean data for the temperature measures are presented in Table 3.1. T_{re} at ExEnd and RestEnd were significantly higher than the Start of each exercise bout within both conditions ($p < 0.008$). However, the T_{re} values were not significantly different between ExEnd and RestEnd within either condition, nor were values different between conditions at any time point. For the T_{sk} values, there was no effect of time or condition. However, according to the Cohen's d procedure, Tsk was moderately higher at ExEnd compared to Start during the CONTROL (Cohen's d = 1.00) and ICE (Cohen's d = 0.89) trials. Shot accuracy score was 33.4 ± 4.0 following the CONTROL trial and 47.2 ± 12.7 following the ICE trial, which was significantly different ($p < 0.05$, Cohen's d = 1.47, Figure 3.2).

DISCUSSION

It is unequivocally accepted that heat exposure negatively impacts athletic performance (27, 2, 4, 8, 38). However, compared to most sports, tennis exposes the athletes to unique thermoregulatory challenges. Tennis involves intermittent periods of high intensity, anaerobic exertion followed by very brief periods of recovery. These activities are often performed in hot temperatures which further challenges cardiovascular and thermoregulatory homeostasis (5, 27). Additionally, atmospheric radiation directly from the sun, as well as reflecting off the court surface, provides a dual heat stress challenge that can further contribute to the accumulating heat strain (5). These unique characteristics of the sport necessitate the need for specific research regarding the effectiveness of cooling strategies among tennis players.

The purpose of this study was to investigate the effects of brief intermittent periods of localized cooling on core body temperature and performance in elite tennis athletes when exposed to exhaustive exercise in a hot environment. It was hypothesized that brief intermittent periods of localized cooling would decrease core and skin temperature and improve shot accuracy. Core temperature significantly increased from the start to the end of the exercise protocols to the same extent in both conditions, but did not return to baseline following 2 minutes of passive rest and the response did not differ between trials. Skin temperature was moderately higher at the end compared to the start of the exercise in both bouts, but the differences of these two temperature measures were not statistically significant. Therefore, it appears that the brief intermittent periods of localized cooling with ice did not mitigate the increase in core and skin temperatures during exhaustive exercise in a hot environment. However, shot accuracy following exposure to the heat stress was significantly better in response to the ice treatment. Therefore, our hypothesis was partially accepted. Intermittent cooling improved shot accuracy following heat stress, but did not slow the rise in core and skin temperatures.

The finding that the application of ice did not slow the rise in body temperature during the exhaustive exercise bout, nor quickened its recovery is possibly due to the limited time that the cooling treatment was applied. In the study, the ice was placed over localized areas (i.e., abdominal wall and thighs) during the simulated 90-second court change over periods of the exhaustive exercise protocol and during the entire 2-minute post-exercise recovery period. These brief episodes of exposure may not have provided a sufficient time period for the cooling to take effect. For instance, Chan et. al. (10) showed a decrease in core temperature in response to exercise in the heat when subjects wore an ice vest during a 30-minute recovery period. In addition, that study found improved subsequent exercise performance, as indicated by increased duration until fatigue, following the cooling intervention (10). On the other hand, continuous cooling did not blunt the rise in core temperature during intermittent exercise nor increase its return to baseline during passive recovery in American football players exposed to heat stress (36). Therefore, more research is needed to determine if various cooling strategies (e.g., continuous versus intermittent versus recovery-only) are not only effective for lowering the response in body temperature, but also practical for competitive athletes.

Interestingly, the cooling treatment resulted in improved shot accuracy, even though there was no significant difference in body temperature responses. These findings may be attributed to factors other than temperature regulation, such as cognitive or perception (35). For instance, exercise in hot temperatures has been shown to impair judgement and decision making, as well as decrease visual sensitivity and reaction time (3, 12, 35). These factors are vital components of optimal tennis performance as incoming ball speeds may reach or exceed 80 mph, forcing the athlete to quickly assess and respond in a precise manner for an accurate return shot. However, Bandelow et. al. (3) showed that intermittent cooling following exercise in the heat lead to faster reaction time and improved visual acuity, independent of changes in core temperature, in competitive soccer players. Furthermore, the cooling strategies may have increased perceived level of comfort and renewed motivation (3), which may also help to explain the current findings of improved shot accuracy following intermittent cooling.

There are some limitations of this study that warrant mentioning. The exhaustive exercise bout was performed on a treadmill instead of a tennis court. However, the high intensity exercise bout was intended to emulate the physiological responses brought on by intermittent tennis-specific activity and has been used in other research on tennis players (19)**.** The shot accuracy phase was performed in a temperate environment as it was impractical to encapsulate an entire tennis court in an environmental chamber. However, the entire duration of the shot accuracy test was approximately 2 minutes which is likely not a sufficient time period for changes in body temperature to affect performance. Lastly, cognitive changes were not evaluated this study. Therefore, future research is needed to address the impact of cognitive function on tennis performance following heat stress.

PRACTICAL APPLICATIONS

This study examined the effects of intermittent cooling on the response in core and skin temperature during exercise in an elevated thermal environment, as well as subsequent performance of elite tennis athletes. The cooling intervention involved ice packs applied around the abdominal wall and the thighs during simulations of between-set periods and court change-overs. The study found that the cooling intervention did not blunt the rise in core and skin temperatures in response to the exercise protocol in the heat. However, shot accuracy was improved following the intermittent cooling. This information could be useful to tennis athletes as well as practitioners and coaches of elite tennis players for potentially improving shot accuracy during match play in hot environments.

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Table 3.1. Participant rectal & skin temperatures of control & treatment condition.

	Start	ExEnd	RestEnd
T_{re} (°C)			
CONTROL	37.3 ± 0.2	38.3 ± 0.6*	38.4 ± 0.4*
ICE	37.4 ± 0.5	38.4 ± 0.4*	38.2 ± 0.7*
T_{sk} (°C)			
CONTROL	33.5 ± 1.2	35.0 ± 1.9	35.0 ± 1.6
ICE	33.9 ± 1.5	35.0 ± 0.9	34.8 ± 1.2

CONTROL = heat stress without ice treatment, ICE = heat stress with ice treatment, Start = start of the exercise protocol, ExEnd = temperature at the end of the exercise protocol, RestEnd = temperature at the end of 2 minutes of passive rest, T_{re} = rectal temperature, T_{sk} = skin temperature. *significant based on an adjusted p value of < 0.008

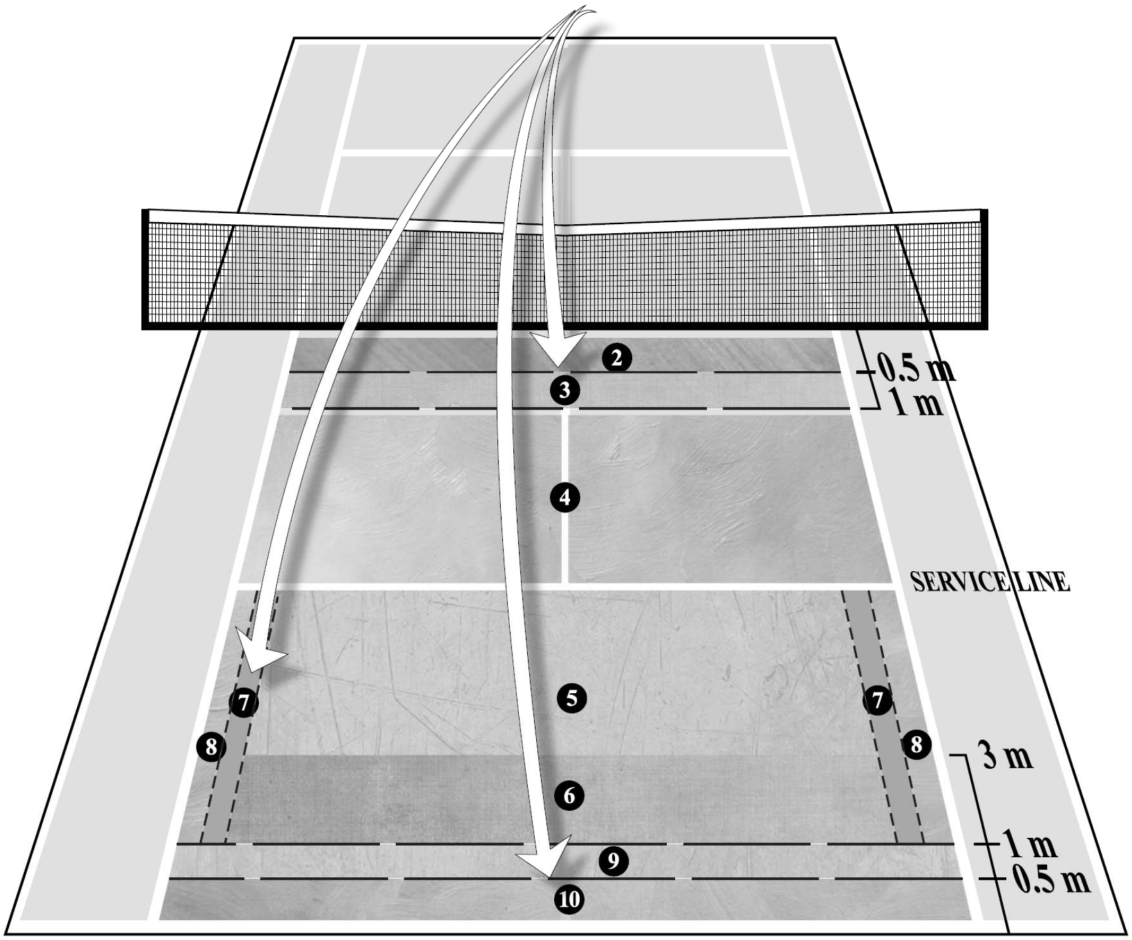

Figure 3.1. Schematic diagram of shot accuracy scoring scale.
Each shot was based on the following:

0 = No successful return. (E.g. ball into the net or out of bounds)
2 = Ball landing 0.5m from the net on and within the singles sideline
3 = Ball landing 1m from the net on and within the singles sideline
4 = Ball landing between the service line & w/in 1m of net and on & w/in singles sideline
5 = Ball landing over 3m inside baseline & b/tw service line on & w/in singles sideline
6 = Ball landing over 1m inside baseline & w/in the 3m of it on & w/in singles sideline
7 = Ball landing on or within 1m inside of the singles side line
8 = Ball landing on or within .5 m inside the singles side line
9 = Ball landing on or within 1m inside of the baseline
10 = Ball landing on or within 0.5 m on or inside the baseline and b/w the singles sideline

The total score of 10 shots was calculated, where the highest possible score was 100 and the lowest possible score was 0.

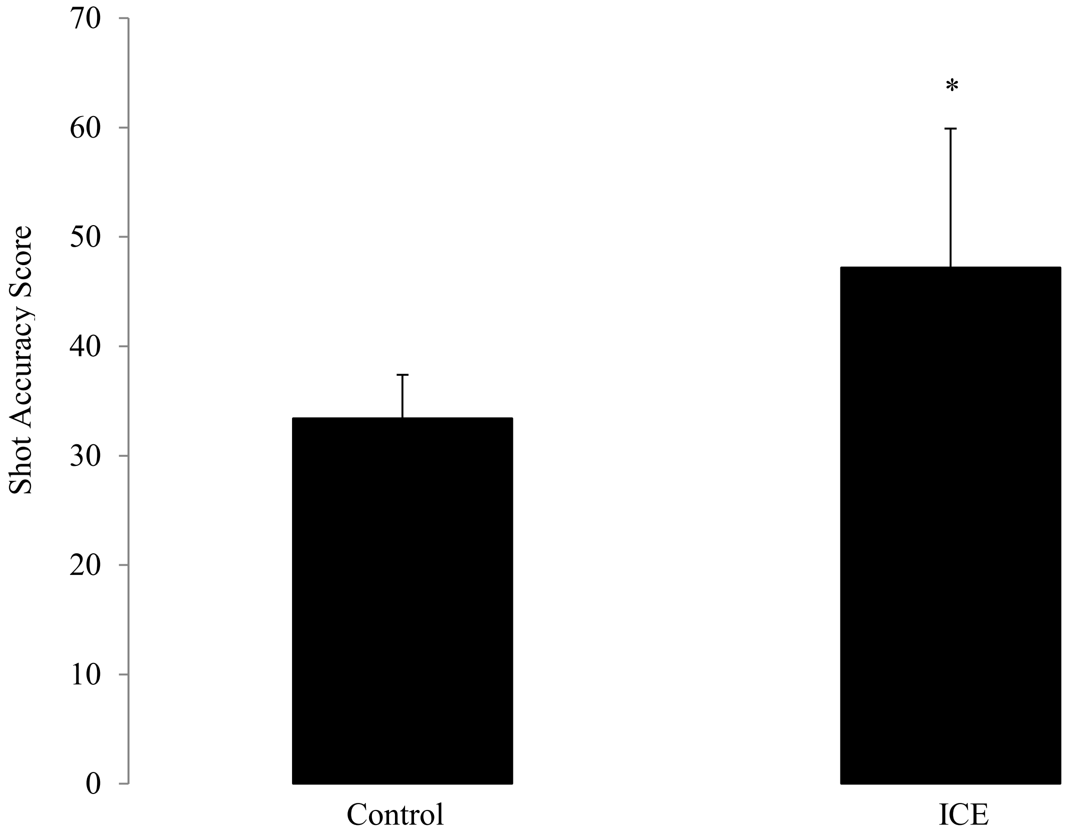

Figure 3.2. Shot accuracy values following the exposure to ice trial and control trial.
*Shot accuracy was significantly better following ICE compared to Control ($p < 0.05$).

CHAPTER 4

EFFECTS OF CONTINUOUS PLUS INTERMITTENT COOLING ON BODY TEMPERATURES AND THE IMPACT ON SHOT ACCURACY IN ELITE TENNIS PLAYERS

ABSTRACT

The purpose of this study was to investigate the effects of a cooling strategy of continuous cooling plus intermittent ice-pack applications on body temperatures and performance of elite tennis players subjected to high intensity exercise in a hot environment. **Methods**: Nine male tennis athletes (age = 20 ± 3 years, height = 183.6 ± 6.6 cm, weight = 74.5 ± 12.5 kg) performed counter-balanced trials of exhaustive exercise simulating the physiological demands of tennis in a hot (37 °C, 38% rH) environment while continually wearing a cooling vest and intermittent ice applications to the walls of the abdomen and thighs (COOLING) and one without (CONTROL). Rectal (T_{re}) and skin (T_{sk}) temperatures were recorded before and after the high intensity exercise bout and at the end of a 2 min recovery period. Following the recovery period, participants performed a 10-point shot accuracy test on an indoor tennis court where each shot was scored and recorded. **Results:** There was no significant difference in T_{re} between the start of the trial and the end of the trial in the COOLING condition; however there was a significant difference in T_{re} at the same time points in the CONTROL trial. The cooling strategy significantly lowered T_{re} during the 2 min recovery phase. Shot accuracy was significantly better in the COOLING condition than the CONTROL condition. **Discussion:** A cooling strategy of continuous cooling combined with intermittent cooling is an optimal method for mitigating thermal strain and improving shot accuracy in elite tennis players.

KEY WORDS: cooling strategy, thermal strain, athletic performance

INTRODUCTION

Compared to other athletes, the elite tennis player is exposed to unique thermal challenges. For instance, matches are normally intense and of long duration with very brief periods of intermittent rest and no substitutions. Additionally, the tennis athlete is subjected to eradiating heat and reflecting solar energy from the court's surface, as well as typical environmental exposures. Furthermore, the tennis athlete has limited availability for the mechanism of convective heat removal due to absence of ambient wind that may be present with running and cycling. These conditions provide added stimuli to the existing homeostatic challenges related to athletic performance in the heat.

Cooling strategies may enhance performance and decrease the risk of heat illness in athletes performing in hot conditions (9, 42). However, a range of cooling options are available, from individual ice packs to full-body cold water immersion tubs, with some more effective than others (14). Continuous application during activity appears to be effective for mitigating the rise in core temperature and performance effects of heat stress (41), yet this strategy may not be practical for tennis players due to the cumbersome nature of most devices. Instead, intermittent strategies have been applied to localized areas, which may not be as effective as continuous cooling process (39, 14, 8) or applicable to the sport because of the long duration of a match. Therefore, finding an unobtrusive wearable cooling device for continuous application may be useful for elite tennis athletes.

Wearable ice vests have recently been developed and touted as a comfortable and unobtrusive continuous cooling garment. However, the limited research regarding the effectiveness of these devices has primarily been performed among tactical professionals, such as military personnel and firefighters (27). Whether a convenient wearable ice vest is effective in elite athletes exposed to hot conditions remains questionable. Therefore, the purpose of this study was to investigate the effects of continuous cooling combined with intermittent cooling applications on core temperatures and performance of elite tennis players subjected to high intensity exercise in a hot environment. It is hypothesized that a cooling strategy of continuous cooling combined with intermittent cooling may be an optimal method to mitigate the rise in core temperature and improve performance.

METHODS

Experimental Approach to the Problem

Nine elite tennis players undertook two counter-balanced testing trials separated by 48 hours. The trials were comprised of high intensity, intermittent exercise on a treadmill in a hot environment. One trial involved a wearable cooling vest and cold packs intermittently applied to the medial and lateral portions of the thigh. Core and skin temperatures were measured during both exercise trials. After a brief passive rest period, the participants performed a simulated tennis bout against a ball machine on an indoor tennis court while wearing the cooling vest. The subject's shot accuracy was measured with an objective 10-point shot accuracy rating scale. Rectal and skin temperature readings and shot accuracy were compared between each trial.

Subjects

Nine healthy male elite tennis players volunteered to participate in this study (age = 20 ± 3 years, height = 183.6 ± 6.6 cm, weight = 74.5 ± 12.5 kg). Participants were recruited from the university's tennis club. The participants were comprised of national tennis competitors. The tennis player participants were considered "elite" because they have been involved in the sport of tennis extensively. They have competed in Division I club play. They had played tennis for a minimum of 10 years, practiced, played and or competed daily. Also they had consistently trained in tennis-specific drills and activities. All of the elite athlete participants had received professional tennis-specific training. Some of the athletes had also lived and trained at professional tennis training centers.

The study procedures were fully explained to each participant and they signed a written informed consent form. According to the pre-screening stratification processes and medical history questionnaire, the subjects were reportedly free from cardiopulmonary and metabolic diseases. The subjects were asked to avoid strenuous exercise for at least 24 hours and abstain from alcohol prior to reporting to exercise trials. Subjects were allowed to eat their “normal” diet; however were requested to avoid food consumption for at least 1 hour prior to participating in the exercise trial bout. The experimental protocol for this study was approved by the University’s Institutional Review Board for research involving human subjects.

High Intensity Exercise Protocol

Participants performed two trials of intermittent high intensity exercise while being exposed to a hot environment (CONTROL) or a hot environment while wearing a cooling vest (VEST) (StaCool Under Vest, StaCool Industries, Inc., Ocala, FL 34482) and with cold ice packs (TruMedical Solutions, Collegedale, TN 37315) applied to the thighs intermittently at certain times during the exhaustive exercise trial bout and during the passive rest period. Both high intensity exercise bouts were performed on a treadmill (Model SOLE 500, SOLE Treadmills Inc., Salt Lake City, UT 84111) in a portable climate chamber that was assembled in an indoor tennis facility positioned immediately adjacent to an indoor tennis court. The portable climate chamber consisted of six modular wooden components that were used to construct a frame (dimensions = 3.86 m in length, 1.91 m in width, and 2.39 m in height). The outer surface of the frame was enclosed with extra heavy duty contractor grade 6 mil plastic sheeting (Contractor's Choice, York, PA 17403). Three 1500 watt ceramic air heaters (Stanley Model 675900, Lasko Corp., Philadelphia, PA) were placed inside of the portable chamber and used during the two trials to heat the chamber environment. The participants wore summer tennis apparel consisting of shorts, a cotton t-shirt, and official "tennis" shoes during each trial bout.

The high intensity exercise protocol was styled from Fabre et al (21) which was created to emulate a tennis match in the form of a series of simulated rallies of treadmill running (The reader is refer to Fabre et.al (21) for further information). The simulated rallies consisted of the following in order: 15 - 30 seconds of treadmill running at a set speed that began at 6.4 kmph and increased by 1.6 kmph during consecutive rallies until 16.1 kmph was reached; 2 simulated forehand and 2 simulated backhand strokes; a 20-second recovery period while standing in the "set position". A series was counted as a full completion of 6 rallies. The first three series were repeated consecutively. A 90-second rest period was allowed to simulate "court changeover" following the third series. The 90 second rest period was repeatedly performed every time a subsequent pair of series was completed. The subjects kept a tennis racquet in their dominant hand during the entire exercise protocol. Match intensity is often regulated on perceived effort (23), because of this cessation of the simulated-tennis exercise protocol was instituted with the Borg RPE 6-20 rating scale. Previously, the highest reported RPE values recorded during individual-play in elite tennis players was 17 (23). For this reason, the simulated exercise protocol was stopped when the subjects reported an RPE of 17. Immediately following the exhaustive exercise trial bout, a 2-minute passive rest period was completed replicating an official "between set" rest period. Both exercise trials were performed in an environment with average air temperature = 36 °C and an average rH = 38%.

Body Temperature Measures

T_c was indexed by rectal temperature (T_{re}) using a copper-constantan thermocouple (Model RET-1, PhysiTemp© Instruments, Inc., Clifton, NJ 07013). Participants inserted the thermocouple approximately 8-10 cm past the anal sphincter. T_{sk} (Model Thermaskin CBL, PhysiTemp© Instruments, Inc., Clifton, NJ 07013) of a single site was measured approximately 10-15 cm measuring inferior to the top of the participant's right shoulder directly down the back, affixed over the participant's right shoulder blade. Both T_{re} and T_{sk} were attached to and displayed by a battery operated portable temperature monitor (ThermAlert Model TH-8, PhysiTemp © Instruments Inc., Clifton, NJ 07013). The temperature readings were recorded at the start of the exhaustive exercise protocols, at the end of the exercise protocol and following the 2 minutes of seated cool-down of the resting phase. The following abbreviations were applied to represent each condition:

Core temperature Metrics of each Condition:

Heat Stress with Vest

- Starting core temperature = T_{re}StartVEST
- Ending core temperature of Exercise Phase = T_{re}ExVEST
- Ending core temperature of Resting Phase = T_{re}RecVEST

Heat Stress without Vest

- Starting core temperature = T_{re}StartCONTROL
- Ending core temperature of Exercise Phase = T_{re}ExCONTROL
- Ending core temperature of Resting Phase = T_{re}RecCONTROL

Skin temperature metrics of each condition:

Heat Stress with Vest

- Starting skin temperature = T_{sk}StartVEST
- Ending skin temperature of Exercise Phase = T_{sk}EndVEST
- Ending skin temperature of Resting Phase = T_{sk} RecVEST

Heat Stress without Vest

- Starting skin temperature = T_{sk}StartCONTROL
- Ending skin temperature of Exercise Phase = T_{sk}ExCONTROL
- Ending skin temperature of Resting Phase = T_{sk} RecCONTROL

Shot Accuracy Test

After the 2-minute passive rest period following the high intensity exercise, participants proceeded directly to the indoor tennis court immediately adjacent to the environmental chamber. The subjects played a 10-point tennis match against a tennis ball machine (Playmate Volley, Playmate ™, Morrisville, NC 27560) while wearing the cooling vest. The ball machine was programmed into an aggressive play mode simulating play against an elite tennis opponent. New tennis balls (Head Penn©, Jeanette, PA 16644) were used for each set of trials. The ball machine had the capabilities of randomized oscillation, consistent targeted accuracy as well as ball speeds approaching and obtaining 129 kmph. The ball machine was placed with the frontal side centered directly over the center mark of the baseline on the opposite side of the court from the player. In order to simulate play against a single elite opponent, ten randomized shots were timed consecutively and sent toward the participant's side of the court. The participant stood behind the center mark on the opposite side of the court behind the baseline at the initiation of the shot sequence.

The returned ball shot accuracy placement of each of the subjects returned tennis shots were measured with a 10-point grading scale. Zero ("0") represented a shot out-of-bounds or into the net, a "5" represented a mid-court returnable ball, a "10" represented an unreturnable ball landing in the very back portion of the court (reader is referred to Figure 1 for a complete description). The scale was designed by the author, a certified tennis professional (i.e. Professional Tennis Registry member #51592), with several decades of tennis play, professional teaching and coaching. The scale was validated by three professional tennis instructors. A single technician blind to the study graded each returned tennis ball for shot accuracy and recorded each score. Ten shots were graded, totaled and recorded as the variable of shot accuracy.

Statistical Analysis

Statistical procedures were performed by the Statistical Package for the Social Sciences (V 22.0 IBM© SPSS© Statistics, Chicago, IL). A 3 x 2 design repeated measures ANOVA procedure was performed to evaluate the difference in both temperature measures across the three time points of the exhaustive exercise protocol (Start, Ex, Rec) and each temperature condition (CONTROL vs VEST). Paired t-tests were used for follow-up pairwise comparisons. A Bonferroni adjusted α level was applied to the follow-up t-tests to reduce the chances of a Type I error when multiple pairwise tests were performed, which resulted in an adjusted α level for significance of the follow-up comparisons was determined as $p < 0.008$. Paired samples t-tests were used to determine the mean differences in shot accuracy between HOT and HV trials, with statistical significance determined as $p < 0.05$. Cohen's *d* statistic determined the effect sizes of the differences in the studied variables (30). Hopkin's scale for determining the magnitude of the effect size was used with criterion thresholds as follows: 0 - 0.2 = trivial, 0.2 - 0.6 = small, 0.6 - 1.2 = moderate, 1.2 - 2.0 = large, > 2.0 = very large (30).

RESULTS

Total exercise time of the exhaustive exercise protocol (i.e., when the subjects reached an RPE of 17) was 27.5 ± 10.4 min for the HOT trial and 32.1 ± 8.1 min for the HV trial, which was not significantly different ($p = 0.300$).

There was an overall significant time-by-condition effect for T_{re} ($p < 0.05$, Figure 2). Pairwise comparisons showed that T_{re}ExCONTROL (38.3 ± 0.6° C) and T_{re}RecCONTROL (38.4 ± 0.4° C) were not significant different, but were each significantly higher ($p < 0.008$) than T_{re}StartCONTROL (37.3 ± 0.2° C). There was no significant difference between T_{re}StartVEST (37.5 ± 0.6° C) and T_{re}ExVEST (38.0 ± 0.7° C), but T_{re}RecVEST (37.0 ± 1.4° C) was significantly lower than T_{re}ExVEST ($p < 0.008$). In addition, T_{re}RecCONTROL was significantly higher compared to T_{re}RecVEST.

For the Tsk values, T_{sk}StartCONTROL was 33.5 ± 1.2° C, T_{sk}ExCONTROL was 35.0 ± 1.9° C, and T_{sk}RecCONTROL was 35.0 ± 1.6° C, while T_{sk}StartVEST was 33.3 ± 0.9° C, T_{sk}ExVEST was 33.2 ± 2.4° C, and T_{sk}RecVEST was 34.3 ± 2.7° C. There were no significant differences in T_{sk} values across the time points or between conditions.

Shot accuracy score was 33.4 ± 4.0 following the CONTROL trial and 46.8 ± 13.1 following the VEST trial. These values were significantly different ($p < 0.05$) with a large effect size (Cohen's d = 1.38). The difference in scores is represented in Figure 4.4.

DISCUSSION

The purpose of this study was to explore the effects of a cooling strategy on body temperature responses and shot accuracy performance of elite tennis athletes subjected to simulated tennis-specific high intensity exercise in hot conditions. The cooling strategy that was employed in the study involved the subjects wearing a continuous cooling vest coupled with periodic applications of ice to the thighs. The cooling strategy was chosen for two reasons. First, the ice vest was an unobtrusive wearable device that provided continuous cooling during play. Second, the intermittent periods of icing the thighs took advantage of the between-set and change-over time frames, as well as providing an additional cooling mechanism. Therefore, it was decided that both methods combined provided an optimally cooling strategy that was suited for the sport of tennis.

The study found that the cooling strategy lowered the T_c response and improved its recovery following heat stress compared to the trial in which no cooling was applied. There was no difference in skin temperature responses between the two conditions. Furthermore, shot accuracy was better following the VEST trial compared to the CONTROL trial. Therefore, it appeared that a strategy of a continuous ice vest plus intermittent ice applications to the thighs is effective for mitigating the negative influence of heat stress on core temperature and performance of elite tennis players.

A recent review concluded that cooling during exercise (also referred to as “mid-cooling” or “per-cooling”) was effective for blunting the increase in core temperature and improving exercise performance (54). However, most of the cooling strategies in the review involved ingestion of cold fluids or cooling the face and neck during exercise (54), which may be impractical for tennis, especially considering the former method may cause gastrointestinal distress (12). The few studies that were available on the effects of continuous cooling via ice vests during exercise have produced equivocal results. For instance, Kenny et al. (36) showed increased time to exhaustion and a lower core temperature while walking in a hot environment with an ice vest in untrained men. Luomala et al (40) showed that average exercise time until exhaustion in the heat was increased by 22% in cyclists while wearing an ice vest compared to the control condition. On the other hand, Eijsvogels et al. (19) found no difference in core temperature or performance between 5-km running time trials in the heat with and without an ice vest in trained runners. These finding cannot necessarily be extended to the sport of tennis, especially since tennis athletes involves a more mixed contribution of anaerobic and aerobic bioenergetics pathways.

Cooling between bouts of activity in hot conditions may lower core body temperature and improve subsequent performance (9, 40). However, most of the research has investigated impractical cooling methods (e.g., cold water immersion) during extended time periods of recovery (e.g., 30 minutes). Tennis athletes only have a small window of time between games and sets (e.g., 90 to 120 s), allowing for only brief periods for cooling in-between active bouts. It has been previously shown that intermittent cooling between brief periods of performance is effective for decreasing core temperature and improving perceived recovery in baseball catchers (6). Therefore, it was decided that the addition of the intermittent ice applications in combination with an unobtrusive ice vest allowed for an optimal and convenient cooling strategy for tennis players during play.

The mechanisms explaining the study outcomes could be related to several factors. The ice vest continuously cooled circulating blood which likely mitigated the rise in core temperature (40). This may have tempered the volume of blood shunted to the skin for heat dissipation, thereby attenuating cardiovascular strain (25). Furthermore, the cooling strategy may have delayed neuromuscular and metabolic fatigue that is associated with exercise performance in the heat. Previous investigations have shown that cooling interventions have enhanced motor-unit recruitment for sustained periods, preserved glycogen content, and decreased circulating lactic acid during exercise in hot environments (48, 58, 35, and 40). Additionally, others have suggested that the effect of cooling on core temperature may be irrelevant to any subsequent performance improvements (54). Therefore, it is possible that non-thermoregulatory factors may have attributed, at least partially, to the improved shot accuracy. For instance, the ice application may have improved psychological factors related to tennis-performance such as attention span (10), judgement (26), decision making (26), reaction time (26), visual sensitivity (26), and motivation (2). Future research is needed to address the specific mechanisms that underscore the impact of cooling strategies for improving performance in tennis players exposed to hot environments.

As mentioned previously, the study utilized a combined strategy of continuous plus intermittent cooling, which took advantage of an unobtrusive wearable vest and the in-between rest periods. Therefore, it is unknown which of the strategies (e.g., vest or ice packs) had the greatest impact. Future research should determine the impact of continuous versus intermittent cooling strategies on body temperature responses and performance in hot environments among athletes.

PRACTICAL APPLICATIONS

The results of this study indicated that a combined strategy of continuously wearing a cooling vest plus intermittently applying ice packs to the thighs during high intensity exercise in a hot environment mitigated thermal strain and improved subsequent shot accuracy in elite tennis players. The cooling intervention in the study may be an advantageous strategy for competitive tennis players as the cooling vest was an unobtrusive device and the intermittent ice applications to the thighs took place during simulated court change-overs and rest periods. Thus, the findings have a number of applications that are worth considering by players, coaches and practitioners in regards to the health status and performance output of elite tennis players.

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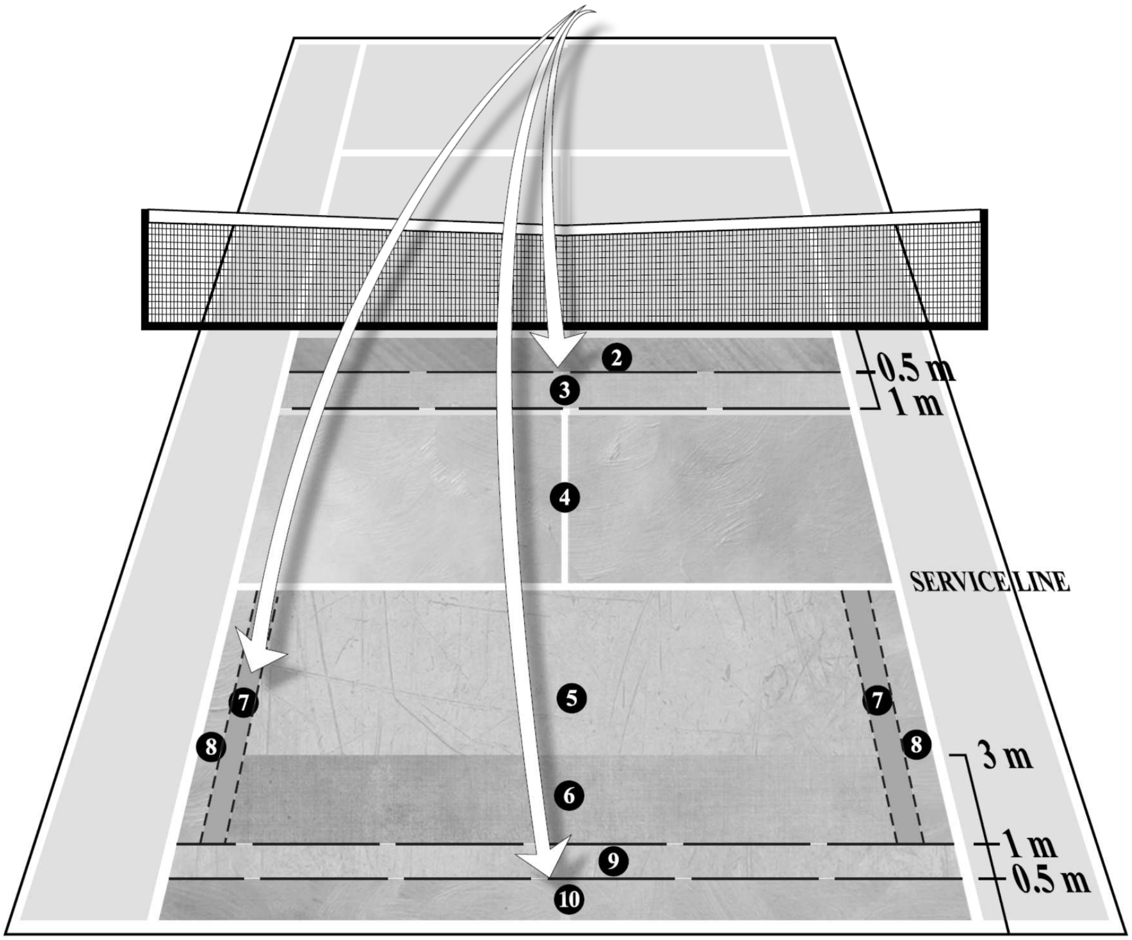

Figure 2.1. Schemtaic diagram of shot accuracy scoring scale.
Each shot was based on the following:

0 = No successful return. (E.g. ball into the net or out of bounds)
2 = Ball landing 0.5m from the net on and within the singles sideline
3 = Ball landing 1m from the net on and within the singles sideline
4 = Ball landing between the service line & w/in 1m of net and on & w/in singles sideline
5 = Ball landing over 3m inside baseline & b/tw service line on & w/in singles sideline
6 = Ball landing over 1m inside baseline & w/in the 3m of it on & w/in singles sideline
7 = Ball landing on or within 1m inside of the singles side line
8 = Ball landing on or within .5 m inside the singles side line
9 = Ball landing on or within 1m inside of the baseline
10 = Ball landing on or within 0.5 m on or inside the baseline and b/w the singles sideline

The total score of 10 shots was calculated, where the highest possible score was 100 and the lowest possible score was 0.

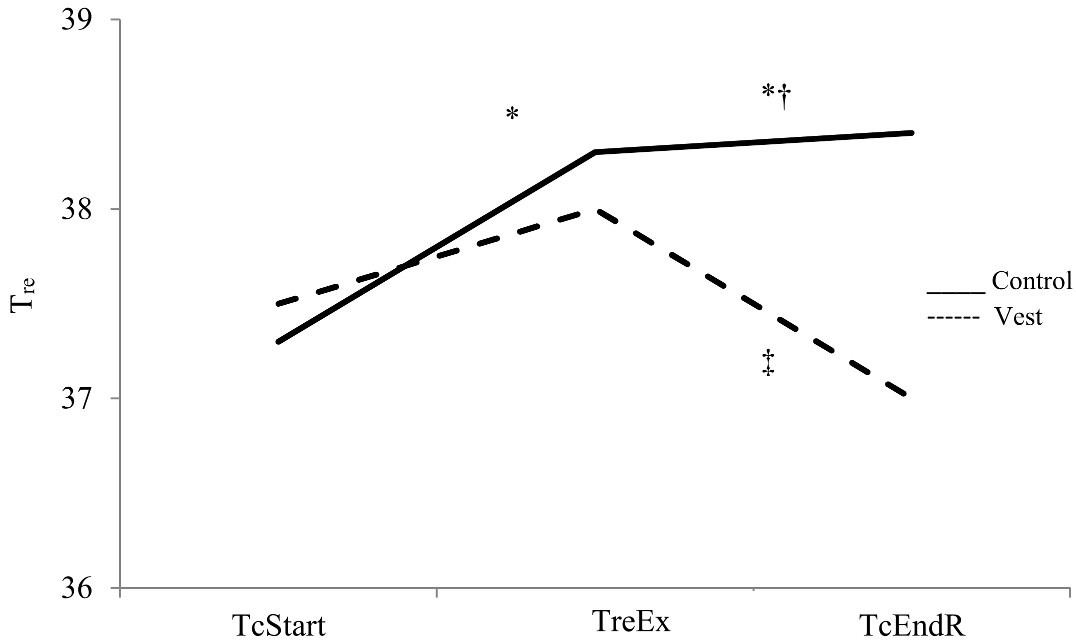

Figure 4.2. Rectal temperature progression throughout the control trial and the vest trial. Vest = Condition with wearable vest and intermittent cooling. T_{re}Start = rectal temperature at the start of the exercise protocol, T_{re}EndX = rectal temperature at the end of the exercise protocol, T_{re}EndR = rectal temperature at the end of the passive resting phase. *significantly higher compared to T_{re}Start ($p < 0.008$). †signficantly higher compared to the Vest at the same time point ($p < 0.008$). ‡ Significantly lower than T_{re}EndEx ($p < 0.008$)

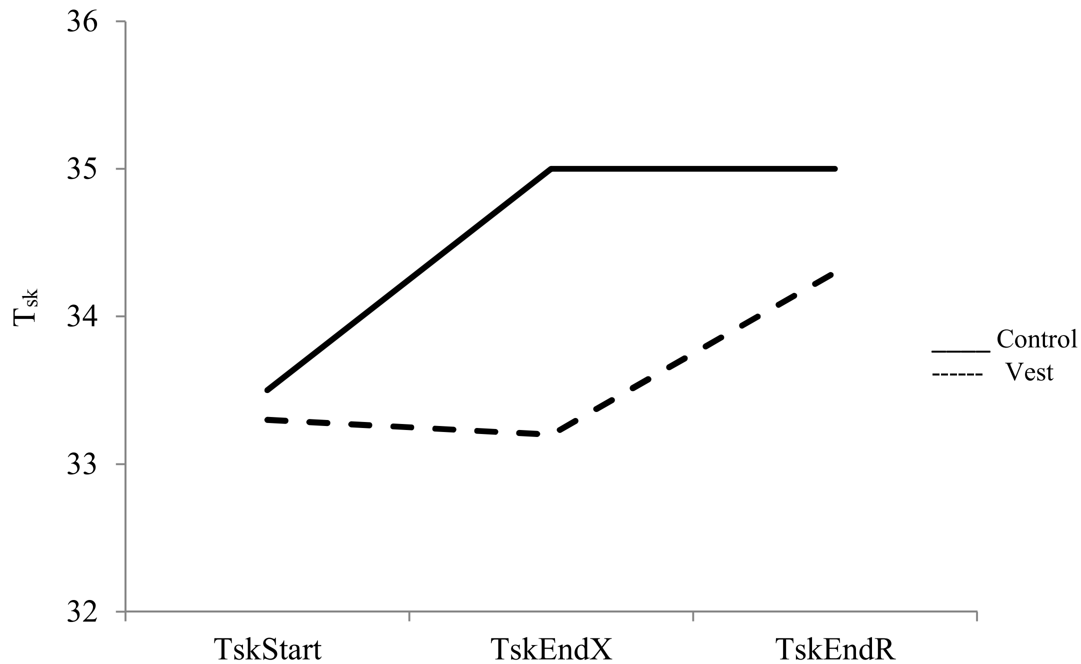

Figure 4.3. Skin temperature progression throughout the control trial and the vest trial. Vest = Condition with wearable vest and intermittent cooling. T_{sk}Start = Skin temperature at the start of the exercise protocol. T_{sk}EndX = skin temperature at the end of the exercise protocol, T_{sk}EndR = skin temperature at the end of the passive resting phase.

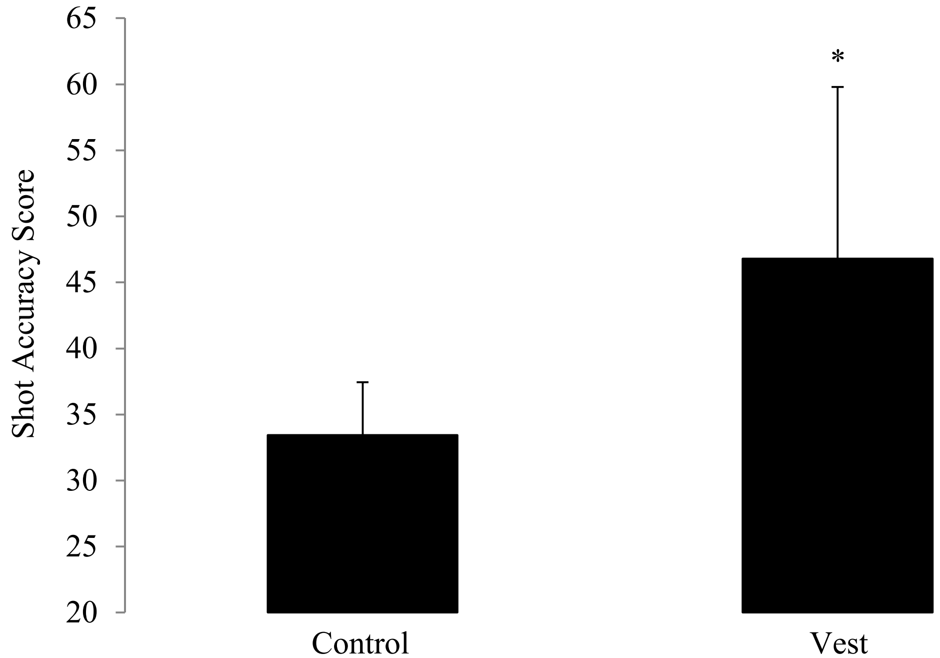

Figure 4.4. Shot accuracy score means of the control condition and the vest condition. Vest = the condition of the cooling vest and the intermittent cold pack applications. *significantly higher compared to Control.

CHAPTER 5

CONCLUSION

Tennis is a sport typically played in hot environments where heat stress proposes dangers to health (1, 2) and negatively affects performance of elite tennis players (6). Matches are usually intense and of long duration with short intermittent rest periods allowing for no substitutions (18). Due to the unique nature of the game, environmental and physiological factors place an increased thermal load on elite tennis players which subject them to an abnormally high core temperature (8, 17, 18). However, the present information regarding the effects of heat stress on players is derived from anecdotal reports in the news media. Scientific examination of this area of tennis is incomplete, as the aims of previous studies on heat stress in sports has focused on runners and cyclists (3, 11). Because of the peculiarities associated with the sport of tennis, the results of previous studies may not be fully applicable (18). Therefore further research is needed to study the effects of heat stress on body temperature and performance as well as examine applicable cooling strategies that may mitigate the effects of heat stress of the tennis athlete. Therefore further research was needed to study the effects of heat stress on body temperature and performance of elite tennis athletes. Previous research on cooling strategies indicated that intermittent and continuous cooling devices have shown positive results in other sports (4, 5, 10, 12, 13, 14, 20) and may possibly have applications to the sport of tennis; therefore these strategies were examined to determine their capabilities in response to heat stress and enhanced performance of tennis athletes.

The first study examined the effects of an acute bout of tennis-specific high intensity exercise both in a hot environment and a temperate environment on body temperatures and performance. It was hypothesized that an exercise bout of substantial duration and intensity in a hot environment as opposed to a temperate environment would significantly increase core and skin temperatures and negatively impact performance.

This study found that the correlation of relationship of the difference in core temperature and the difference in shot accuracy between the 2 trials indicated to be *near perfect* and significant. Shot accuracy performance was observed to be significantly worse in the hot trial, furthermore the hot environment affected the higher performing players the most by having the greater decreases in shot accuracy in the hot trial.

The purpose of the second study was to investigate the effects of brief periods of local cooling applications in the form of ice-packs on body temperatures and performance when the athletes were exposed to an exhaustive protocol in a hot environmental chamber. It was hypothesized that the intermittent ice pack applications would blunt the rise in core temperature and possibly improve performance.

The results of this study showed that the brief periods of localized cooling with ice did not mitigate the increase in core and skin temperatures. However, shot accuracy performance was significantly better in response to the ice treatment.

The third study investigated the effects of continuous cooling in the form of a wearable cooling vest combined with intermittent ice pack applications on core and skin temperatures and the impact they had on performance of the tennis players subjected to the tennis-specific high intensity protocol in hot conditions. It was hypothesized that the combination of intermittent cooling coupled with a wearable continuous cooling device may be the most optimal method for lowering core temperature and enhancing performance.

The results of this study indicated that a combined strategy of the continuous ice vest plus ice applied to the thighs intermittently was effective for mitigating the negative influence of heat stress on core temperature and performance of the participants. This strategy lowered the core temperature response and showed improved recovery following heat stress compared to the trial in which no cooling was applied. Performance in the form of shot accuracy was significantly better following the trial with the combined strategy compared to the trial without.

The collective findings of this dissertation demonstrate that there is a near perfect relationship between core temperature and shot accuracy performance of elite tennis athletes and that shot accuracy is significantly worse in a hot environment. Additionally, a combined strategy of cooling interventions appears to be an optimal method to mitigate the negative effects of heat stress by lowering core temperature; therefore improving performance and decreasing the threat of exertional heat illness in elite tennis athletes.

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